EVALUATION OF ROAD CONSTRUCTION ALTERNATIVES:

A REGRETFUL APPROACH

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Evaluation of Road Construction Alternative: A Regretful Approach

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ABSTRACT

This study's objective is considering two main innovative criteria in evaluating alternatives of different road designs. It focuses on regret theory and its utility in evaluating between different alternative designs and develops new criteria in the assessment of a traffic safety performance indicator.

Decisions between different road construction alternative designs are based on multi-criteria factors. This research develops a systematic methodology in considering regret based on a weighted system of performance indicators that include, planning, traffic flow, traffic safety, construction economics, and time. Due to uncertainty, a process to formulate a regret matrix is developed that introduces criteria to evaluate between different alternatives. A full set of procedures for developing the matrices are classified. Sensitivity of weights on the overall results is also tested to ensure reliability of subjective quantities.

Meanwhile, most research studies today for evaluating road designs emphasize in traffic flow more than traffic safety. A technique that allows for the quantification of a performance indicator for traffic safety is proposed, based on direct factors and the likelihood of conflict in a microscopic level. The performance indicator for traffic safety is included in the regret matrix for the evaluation between different road design alternatives.

This abstract accurately represents the content of the candidate's thesis. I recommend its publication.

Signed [redacted]

Bruce Janson

DEDICATION PAGE

I dedicate this dissertation to all humanity and creation, for all have inspired my thoughts every moment in life.

ACKNOWLEDGMENT

I would like to thank everybody who has supported me throughout my life.

"Oh my Lord, advance me in knowledge" (Holy Qur'an 20:114)

"Surely you desire truth in the inner parts; you teach me wisdom in the inmost place." (Psalm 51:6)

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1.1 Overview

Automata revolutionized how humans work. Machines have taken over the jobs of humans, and the purpose is not to increase unemployment rates, but to allow human minds to invest more time in more important thoughts than menial tasks. The definition of a menial task changes from one generation of technology to another. This allows humanity to progress.

Judgment is a very subjective affair. Experts make judgments based on their past experiences. Experts become experts due to their experience. Experience is derived from the learning curve. The learning curve is a function of time. Therefore, it takes time to make good judgments, and judgments are fallible due to human error. Though the human mind is very complex and can analyze much data very quickly and mostly subconsciously, it is always prone to biases in cognitive psychology. Hence, it is difficult to *judge* whether or not a judgment is fair. That statement in itself is a self-defeating loop to prove how subjective judgments can be.

Machines, on the other hand, are made to work based on a system. Of course, the system might be made to be biased, but generally, everyone subject to that system will be treated fairly. To elaborate more on that, it means that if two events having the same criteria occur, then the system will always give them the same outcome.

For example, if a traffic police officer is controlling traffic in a busy intersection, then the judgments of the officer will vary. When all vehicles in one leg has been serviced, but a car is coming not too far away, the police officer might wait to allow that car to go through and delay vehicles in crossing legs, as the officer's decision might be subject to human emotions. At another cycle, if the same event occurs, the police officer might actually stop the one car, and allow other vehicles on crossing legs to go through. However, when a signalized intersection exists, then the outcome will always be the same for any event meeting the same conditions. The main reason is because it functions through a system independent from any psychological or physiological factors that might affect how a human being might make decisions.

The circulatory system of a human being is important as it transports oxygen and nutrients to various cells in the body such that organs can remain healthy. Similarly, in an urban area, the transportation system transfers goods and services to ensure the health of the economy between all the different land uses. The ultimate cause of having a transportation system is therefore not to transport between origin and destination. The transport itself is just the methodology used to reach the ultimate goal, which is sustaining a healthy economy.

Decision-making in the public sector is vital. Transportation is usually a significant issue discussed by politicians promising projects alleviating traffic congestion or reducing environmental impact of traffic.

The main reason why transportation is very important in the political arena is because the economy is directly related to the transportation infrastructure. Making a decision on what roads to construct or re-construct and how to re-construct them can and will cause the economy to either boom or deteriorate.

Those decisions may also cause the popularity or defeat of a political candidate. In today's world of technology, complex decisions pertained to traffic engineering can be thoroughly analyzed by a system such that a decision can be made only after a comprehensive study. If a decision for a road construction project is well studied, then the combination of traffic flow, cost, and time (sustainability) is at optimal performance.

Decisions are usually plagued by a disease known as uncertainty. Uncertainty is a barrier to predictability. It is difficult to predict uncertain events. What is even more difficult is to decide among actions with uncertain outcomes. What is further more challenging is to quantify the regret factor if a decision would be regretted due to the uncertainty of the outcomes.

1.2 Problem-Statement

Decisions pertaining to road construction projects are complex. Since roads projects are usually budgeted from public funds, the risk is high to the government, especially since those projects are multi-million dollar projects. There are associated risks of going over budget due to unstudied decisions or *uncertainties* whether in the short- or long- terms.

Human beings need as much data analyzed to get more accurate results. Otherwise, statements such as that said by Lord Kelvin, President of Royal Science Society, in 1895, "Heavier than air, flying machines are impossible," would have never been said. In less than ten years, a flying machine took-off.

There are limited systematic methods to formulate decisions of road constructions. Mostly, decisions are restricted by current budgetary requirements and making the best traffic flow that suits the budget, **OR** the traffic flow problem is looked at and a budget is requested from public funds to solve the traffic problem. Usually, this method is ad-hoc and does not consider several aspects, such as how much will the new construction affect the environment or nearby businesses, or whether the road is expandable in the future or not.

Due to restrictions, which may or may not be intended, such as uncertainties or those due to budget constraints, any decision may be regretted. However, most current models do not include the regret factor in the decision process, which is highly important.

Defining regret is somewhat complex. As a short overview of decision theory and regret theory, the following example gives a simple illustration of what regret could mean.

Imagine you fill your car with fuel from a gas station. After you travel a short distance you find another gas station that is selling the fuel at a cheaper price. Therefore, you may regret your initial decision, because it

was not very economical, financially. However, this statement is not completely true. Although you had no idea if there were going to be another gas station in a short distance, and if there were one, you had no idea how much the price of fuel would be. The price could be the same, more, or less. However, that does not mean you cannot devise different strategies. A few of which could be the following:

1. You could have researched where the cheaper fuel is located, but that will waste your time and time is money. So your effort may not be worth the extra amount you might pay if per chance you chose to go to the more expensive gas station. You may or may not regret your decision. Your regret will increase the more money you might have saved.
2. If there is an equal probability that the first gas station is cheaper or more expensive, then you can fill in the first. If you find the second gas station is cheaper then you will regret your first decision. However, if you do not know whether another gas station exists, then not filling up in the first gas station will be even more regretful if you later find that there were no other gas stations nearby.
3. On the other hand, your initial conditions are very important. If your fuel tank is almost empty, then you will decide to fill in the first gas station you find without any regret, whether or not you know the second gas station exists and is cheaper.

This is a quick illustration of the how regret theory, which is an integral part of decision theory, helps in understand the decision process that is

followed when deciding between different strategies. Many transportation planning models do not include regret.

Transportation planning models are widely used throughout the world. Many transportation models include mass transit systems in highly populated urban areas. Traffic models are also utilized to allow decision-makers further understand traffic impact and traffic flow. However the majority of traffic models focus primarily on traffic flow. The popular performance indicators used by traffic models are measures of effectiveness of the traffic flow. In the core essence of traffic models, traffic safety is usually neglected.

1.3 Aim and Purpose

The goal of this study is to further refine current transportation models when comparing different road designs within a Geographic Information Systems (GIS) framework to include two main issues that are found lacking in current systems. The purpose is to formulate performance indicators with the inclusion of a matrix for the regret factor in the decision-making process and to build performance indicators for a traffic safety model. This refined model allows the system to assist in analyzing different roads construction alternatives to aid in decision-making. Although the model is based on decision theory techniques, it is only meant to aid a decision-maker and not make the decision on its own. This is due to legal and contractual requirements. If the decision made is incorrect, the system cannot be held liable. Therefore, responsibility of the decision will be held by the decision-maker and not the system (i.e. you cannot sue the system).

Geographic Information Systems (GIS) is a tool developed to aid in analytical processing of geographical data. In reality, all data is location-based. If spatial data to select the best location for a supermarket is analyzed, then GIS may be used. That however, will not be any different than to create anatomical models in GIS to understand the best location for surgical incisions to remove a tumor. Just as GIS is capable in analyzing traffic flow in a road network, blood flow in the human body is also a spatial representation. Just as analysis of gravitational fields of celestial bodies is a spatial depiction, so is the same in the atomic and quantum level. Hence, if the system needs to analyze data, a spatial representation would definitely be as important. The exquisiteness of the system is that no matter how many databases are required, they can all be linked into a spatial database that GIS provides.

Why GIS?

- Roads are spatial data
- Features affected by road constructions (vegetation, businesses, traffic, etc) are also spatial data
- Construction cost and other costs are usually non-spatial data
- Therefore, GIS is best used to develop a model that can analyze both spatial and non-spatial data by creating a relational database by virtually putting layers that are found in reality

There are different modes of decision-making, i) calculation-based, ii) rule-based (conditional), and iii) affect-based decisions. Also, processing

information can be done analytical or experiential. Nonetheless, though they seem different, they are actually the same. What human beings call experience, in the language of mathematics, it is called statistics.

In human experience, decision-making has several constraints that include cognitive and motivational constraints. Cognitive constraints stem from bounded rationality (Simon 1957). Because of memory and attention limitations, people are selective in what and how they process information. A similar constraint can be found in a system due to system capacity and time. Thus, heuristics tend to simplify how information is processed, even through a system. Motivational constraints results due to conflicting goals and strategic distortions. Selectivity of attention and interpretation of uncertainty are often biased, and if not, are to the very least prone to it.

Due to uncertainty, there is room for regret. Therefore, probabilistic modeling is used to further understand the regret factor. Variables of uncertainties are defined in this study. Those variables form the basis of any roads construction study and models that are used today. They include traffic data, transportation data, since major urban cities move towards multi-modal transportation networks, geotechnical data, especially important when the roads project involves the construction of tunnels or bridges, buildings in the surrounding areas, environmental data that would possibly be impacted by different road construction alternatives, utilities data, as it forms an integral part of the road corridor, planning data to ensure that the planning of surrounding area can integrate the new roads construction seamlessly or whether certain

conditions would be important to meet some requirements, such as building noise walls separating the highway from residential areas, as well as the possible effects of the zoning of the area, and of course, financial data, which, to many authorities, is the real and final decision-maker, no matter what other variables might conclude.

Another highlight of this study is the time variable. It is sometimes more important to complete a project in a certain timeframe than the project itself. From the example illustrated earlier about the gas station problem, your initial condition of how empty your fuel tank is would make you take a decision even you knew it would not be financially the best. Similarly, some roads projects might wait years or even decades to complete, while others need to be completed as soon as possible no matter at what cost. This study looks over the factors that would conclude such events and how regret can affect those variables, and therefore the decision process.

Due to the fact that most decisions involving construction of road alternatives are usually based on performance indicators based on traffic flow, this study also dwells in introducing a methodology for constructing a performance indicator for traffic safety. Traffic safety is a very important criterion when evaluating different road design alternatives, however, very few studies exist in quantifying a performance indicator for that purpose. Thus, it is imperative to construct a performance indicator that evaluates traffic safety in this study to be included alongside other criteria models.

1.4 Limitations of the Model

The model introduced in this study is intended to quantify the level of regret of decisions pertaining to the choice of different alternative road designs. It is best utilized for design of an intersection, segment of road, or highway within a limited geographical area, in order to decrease the level of bias between the data available for each alternative. This means that if there were data missing, it would be missing on all alternatives. As with any model, the accuracy of the results is dependent on the accuracy of the data provided. However, the model proposed in this study has the capacity to consider the regret due to lack of information or misinformation by quantifying the confidence level within the regret matrix. In other words, the results would quantify the level of accuracy expected from the model.

The model is not intended to outline a strategy for decision-making. It assumes that a strategy has already been assessed by decision-makers through strategic planning and goals. Thus, once a decision for a new road or the reconstruction of an existing one has been established and there are different alternative designs for the road, then this model has the capability to translate those designs into quantifiable figures and compare the best alternative, based on the strategy applied by the decision-makers by providing importance levels to different performance indicators. However, the model does provide a basis to start developing on optimization of the strategy used, which can be used as a starting point for further optimization research. It is possible to regret the strategy used and the model proposed in this research looks into the sensitivity of

the model due to regretting the strategy applied to reach a winning alternative.

For example, if a specific intersection has a high rate of crashes and engineers in the city plan to re-design the intersection, then this model can be used to choose between different designs, after the goal of enhancing safety has been established. The decision-maker would be able to provide a higher weight for traffic safety and a little lower on traffic flow, since their goal is to reduce the number of crashes, and not necessarily enhance the traffic flow, which may not even be a problem with the current design.

1.5 Study Outline

The outline of this paper starts with a literature review discussion in Chapter 2 along with some details from different case studies. GIS models to understand the multi-criteria nature of decision making for road construction alternatives are introduced in Chapter 3. The core of this study, the evaluation of regret, is discussed in Chapter 4. Since this study introduces the evaluation of regret factor of different criteria involved in the decision making of road construction alternatives, the main focuses for these indicators are i) planning, ii) traffic flow, iii) traffic safety, iv) construction economics, and v) time. Available models for planning are reported in Chapter 5. It introduces possibilities of evaluation due to different planning criteria, such as land use and land valuation, as well as environmental aspects of the decision-making, including development growth or densification. Traffic flow analysis is placed in Chapter 6, along with different models in the evaluation of

performance indicators for that purpose. Chapter 7 is another highlight of this study as a traffic safety performance indicator is constructed. Construction economics and the effect of time in the evaluation of different performance indicators are presented in Chapter 8. A final conclusion for the culmination of this study is placed in Chapter 9 with notions for future research.

2. Literature Review

2.1 Introduction

In this chapter, comparison of different study areas in the world regarding decisions made in road constructions will be considered to better understand the model to be developed. Literature review of previous studies made in the subject matter will be reflected upon for further deliberation to construct the GIS model for decisions pertaining roads construction.

Within the framework of this study, four main cases will be considered, 1) 'Big Dig' project in Boston, MA, 2) reconstruction of 6 interchanges within a short period of time along the same highway in Dubai, UAE, 3) highway controversy in Plzeň, Czech Republic, and 4) Dublin port tunnel project in Dublin, Ireland.

The performance indicator under study is a combination of traffic, cost, and time. This section looks at available literature of how different types of numbers are combined, since traffic delay, cost, and time have completely different units.

2.2 GIS Modelling and Decision Approach

GIS, as a tool of decision support systems (DSS), is not meant to take place of a decision-maker, but to be utilized by a decision-maker. Reasons for this are further discussed in this study. Typically, GIS in a

government environment is seen as a set of tools (Burrough 1986), which provide both infrastructure and business application services (Chan and Williamson 1995).

Within a geographic database, spatial and attributed objects are related with each other to create a complete data model (Zeiler 1999). Tomlinson (2003) considers the totality of a GIS model as an actual structure of data done by using several logical data models that include relational, object-oriented, or object-relational. The transport model is a mathematical model that is constrained geographically and the transportation system within a specific area (Israelsen and Fredriksen 2005).

GIS can handle spatial data as well as attributes within a single system. Thus, it is a powerful tool that combines the analysis as many datasets as a system can handle (Batty and Xie 1994a, 1994b, Sui 1998, Yeh 1999). In many industries, GIS is used for its visualization capabilities, while its modeling capabilities are relatively underutilized (Klosterman 1998, Nedovic-Budic 1998, Wegener 1998). Jha et al. (2001) suggest that GIS serves as the main source for data utilized by genetic algorithms (GAs) to optimize highway alignments.

In this study, different methods of implementation of the GIS model are examined. Since the GIS model incorporates many different data sets and analysis, one possible method is having different GIS linked with each other, but the question remains is interoperability. Goodchild et al. (1997) and Bishr (1998) suggest the necessity of interoperability at

different levels between systems. Interoperability is the freedom to mix and match different components of an information system, such as software, hardware, networks, data, workflows, process, and human interface, without compromising the overall success. Interoperability is the communication and coordination between two or more entities which have a different model and language, such as application program, objects, and system environment.

Risk and uncertainty are fundamental factors in decision-making. Hardaker et al. (1997) define uncertainty as imperfect knowledge, and risk as uncertain consequences. Some researchers, however, use terms, risk and uncertainty, interchangeably (Pannel et al. 2000). Some theorists make no distinction between both terms (Norman and Shimer 1994). Van Asselt (2000) considers both terms as a consequence of limited predictability as a result of complexity.

In dealing with GIS, Rowe (1994) classifies uncertainty and variability into four main classes, metrical, temporal, structural, and translational. Metrical uncertainty defines the uncertainty of measurement. Temporal uncertainty relates to the uncertainty of future and past states of nature. Structural uncertainty entails complexity of the model structure. Translational uncertainty identifies the uncertainty of results.

Various research exist on spatial uncertainty and methodologies of dealing with them, especially as GIS models tend to simplify real events (Agumya and Hunter 2002, Crosetto and Tarantola 2001, Davis and Keller 1997, Heuvelink 1998, Zhang and Goodchild 2002). Agumaya and

Hunter (2002) define the impact of risk assessment by uncertainty of geographic data, which is necessary in examining different roads construction alternatives.

When creating a GIS mode, different factors are considered, each having a different dataset. Since Ferson and Ginzburg (1996) suggest that uncertainty arises from ignorance or variability in the decision-making process caused by factors that are not considered in a decision, and since it is not possible to have a perfect GIS model that considers absolutely everything, based on Gödel's incompleteness theorem, which proves that every formal system is incomplete (Jongeneel and Koppelaar 1999), then a probabilistic model is necessary, and therefore, brings this study into the world of decision theory techniques (Edwards and Fasolo 2001). Jungermann (1983) even shows that not only systems, but experts may sometimes make inconsistent decisions.

Since this study considers a decision flow process that examines different alternatives of roads construction, a probabilistic model within GIS, would therefore be scrutinized. This is based on the arguments of Tverskey and Kahneman (1974) and Shafer and Pearl (1990) who consider decision makers to think of likelihood of different outcomes occurring. Therefore, probability theory should be used to formulate the reasoning under uncertainty.

In spatial topology, concepts of fuzzy logic are derived from Zadeh (1965). Bonham-Carter (1994), Corner et al., (2002), and Pearl (1988) discuss probabilistic models that are useful for GIS decision flow path. A

'what-if' method suggested by Dittmer and Jensen (1997) analyzes the change in outcomes if the state of one variable is changed. For example, the time constraint in construction might be threatened due to some uncertainties such as a storm in the construction site, or even a storm somewhere else geographically that affects the shipment of construction material required. Corner et al. (2002) introduces the term 'map purity' that is defined as the probability that a classification in a dataset is a true classification on the ground and can be derived directly from experts or from metadata.

There are numerous studies about that pertain GIS models for traffic analysis. However, many of those studies focus in the environmental aspect of urban traffic, such as air and noise pollution. Traffic modeling is a field in traffic planning that has made most use of GIS (Nielsen 1995).

Translating data between GIS and traffic models is sometimes represented in Graph-theory. Minieka (1978) represents a traffic network as a graph to feature an optimal implementation of the All-or-nothing algorithm. Usually, to assign traffic on the network, the all-or-nothing algorithm should be run in an iterative process (Daganzo and Sheffi 1977, Sheffi and Powell 1982, Sheffi 1985, Nielsen 1996, 1997a, and 1997b). Traffic assignment of link-node-turn topology for traffic data has been classified for intersections by Nielsen et al. (1997a, and 1997b).

Many studies are available in literature that provides GIS-based models for noise pollution of traffic networks. Uesaka et al. (2000) introduced a

statistical method to estimate noise level in urban areas. This method is adopted by Acoustical Society of Japan's 1998 road traffic noise prediction model (ASJ Model-1998). Another simulator, DRONE (area-wide Dynamic Road traffic NoisE simulator) has been developed by integrating traffic flow characteristics with noise modeling (Bhasakar et al. 2004). The integrated tool has been linked to provide contour maps within GIS. Current models help in understanding the need of different GIS data that is necessary, such as buildings data to calculate multiple diffraction and reflection between buildings. McDonnel and Chung (2001) have also argued the effects of noise pollution also have an economic impact derived from the reduction of property value when doing a cost-benefit analysis. Thus, this has a hefty impact when planning new road construction projects, and therefore should be considered in the performance index. Tachibana (2000) and Oshino et al. (2000) have presented calculation models that are plausible for implementation within GIS framework for noise pollution presented by traffic.

Miotto (2000) identifies certain GIS layers necessary in GIS to evaluate cost-effective highway corridors, such as flood-plains, wetlands, and watersheds. Recent studies have shown Genetic Algorithms (GAs) as an effective tool to search for a minimum cost highway alignment while satisfying design requirements (Jong 1998, Jha 2000, Jong et al. 2000).

Jha (2000) developed an optimization model based on cost minimization for highway alignment. McCall (1999) developed a cost-effective GIS technique for visualization of highway applications which includes 2D

overlays, 3D surface and terrain visualizations, photorealistic rendering, animation, real-time simulation, and virtual reality.

As decision theory is based on an expected utility function, regret theory is based on non-expected utility function, first proposed by Bell (1982) and Loomes and Sugden (1982). Compared to different non-expected utility theories and under uncertainty, regret theory is consistent with violations of transitivity and have been observed experimentally (Loomes et al. 1991). Other theories, such as the prospect theory, are not consistent with violations of transitivity (Kahneman and Tversky 1979, Tversky and Kahneman 1992). Many studies have tested the predictions of regret theory in a qualitatively.

The relationship between regret and decision process are intertwined. Larrick (1993), Zeelenberg et al. (1996), and Zeelenberg (1999) have provided psychological evidence on the impact of regret on decision making under uncertainty. Although regret has not been analyzed in decision making for road construction in particular, as well as expected traffic flow and safety, it has been analyzed for its role in medical decision-making (e.g. Smith 1996, Yaniv 2000). In terms of construction cost, regret theory has been incorporated into models of asset pricing and portfolio choice by Gollier and Salanié (2006) and Muermann et al. (2006).

Regret theory has been used to explain stock market investments (Barberis et al. 2006). Hedging behaviour has also been shown to be due to regret (Michenaud and Solnik 2006). Regret has also been found

to explain disposition effect, where investors may sell winning stocks and hold losing ones (Muermann and Volkman 2007).

Some researchers have argued in favour of the perspective validity of regret theory and intransitive choice (Loomes and Sugden 1982, Bell 1985, Anand 1987, Fishburn 1991), while others oppose this argument due to the possibility of intransitive preferences. Nevertheless, in this research, it is crucial to define a method that allows quantifying regret theory for practicality.

Quantification of regret has been introduced in several ways. Some research suggests that a trade-off method similar to that used in prospect theory to quantify utility may also be used within regret theory (Wakker and Deneffe 1996).

Error propagation proposed by Fechner (1860/1966) has been modeled in decision theory by Hey and Orme (1994) and successfully applied in behavioural game theory (McKelvey and Palfrey 1995, Goeree et al. 2003).

2.3 Traffic Performance

The main purpose of roads construction is traffic flow. Transportation networks are an integral part of any society. Traffic congestions can be analogous to vascular clogs due to diseases, which can affect the human health significantly. Similarly, traffic congestion affects the health of society in various terms, such as social, economic, etc. Hence,

evaluating the performance of traffic is very important in the decision-making process.

Road networks in urbanized areas include freeways, traffic signals, and the traffic assignment between them. Since this study does not specify the type of road construction, an inspection of various methods could be included within the GIS model. The type of GIS data required for each is studied to give a comprehensive analysis.

Predicting traffic flow using relative models is a common approach. Prediction models originally developed by Webster to predict delay at signalized intersections considers uniform delay caused by the traffic signal and random delay due to signal failure caused by vehicle queuing in advance of the intersection and the inability of the intersection to clear all waiting vehicles (TRB 2000). The 2000 Highway Capacity Manual (TRB 2000) considers delay models similar to Webster's to calculate delay-based Levels of Service (LOS) to be used as standard features for planning, design, and operational timing of intersections.

Models used to measure capacity or quality of service is relative and not exact. It is unlikely that any intersection would produce delay that replicates exactly as those measured by HCM or Webster's model. Typical error between modeled and actual delay-based Levels of Service can be extensive, and yet this poor accuracy is still acceptable.

Traffic performance does not only consider traffic flow, but also traffic safety. Both are essential to quantify the cost of different road

alternatives. In much past research, the safety aspect of roads is not given its rightful consideration (Hauer 1992). This research considers both traffic flow performance and safety as part of the decision-making procedure that the GIS model discussed needs to handle. The matter is not that traffic safety is not important by most researchers, but the difficulty to quantify a prediction model for accidents. The most common traffic safety prediction models have been regression models that produce accidents per million entering vehicles for intersections or accidents per million vehicle miles of travel for highway corridors. However, the statistical models used cannot be transferred to other sites as each site is unique.

Several studies have reported at-best 20% accuracy of impacts, effects, and correlation of actual on-site annual accidents (McGhee and Arnold 1997). The definition and observation of any on-road event is subjectively unique among both drivers and observers, as it is influenced by human, vehicle, environmental, and other conflicting factors. According to FHWA (1995), the reliability of accident data also varies staying at an average of 60% – 70% reliable.

In most cases when evaluating traffic performance, the majority of the performance is done based on traffic flow. A performance indicator for traffic safety is rarely utilized when evaluating alternative designs. Hence, this research goes further into investigating and modeling a performance indicator for traffic safety. It quantifies the different factors that affect traffic safety performance on different road designs.

2.4 Cost Estimation Methods for Construction

The calculation of cost is divided into 3 main branches,

1. cost of construction
2. cost of mitigation
3. maintenance cost

Estimating roads construction cost had been achieved in several basic methods in the industry. Unit rates of construction, such as the cost per lane mile have typically been used to estimate roads construction cost in the short term (Hartgen and Talvitie, 1995; Stevens 1995). This method, however, does not take into account data that this study focuses on for a GIS model, such as topography, geology, planning, environment, and traffic.

Another method used is by extrapolating past trends, or time-series analysis, to forecast future projects (Koppula 1981; Hartgen et al. 1997). This method, in general, collapses into a single overall expression of construction cost, such as the FHWA CBPI or the Engineering News Record's Building Construction Index (ENR BCI) or Construction Cost Index (ENR CCI). Nevertheless, these methods would still not be very reliable, since the location of the construction has a great factor of the cost. This method would be useful when comparing roads construction of a large jurisdiction, such as a statewide comparison.

Since this study considers a GIS model for decision-making, the data required for the GIS model would affect the analysis of cost. Hegazy and Ayed (1998), for example, have found that season, location, type of

project, contract duration, and contract size had a considerable influence on individual contract costs. Herbsman (1986) concluded that the volume of contract bids each year impact contract costs, besides costs of material, labour, and equipment. Herbsman argues that competition for the bids influences contract costs. On the other hand, Olsen and Epps (1981) also found that variation in bid volume from year to year affected bid prices. Koehn et al. (1978) and Elhag and Boussebaine (1998) have determined that government regulations, plan changes, quality of the contractor's management team, priority on construction deadlines, completeness and timeliness of project information also impact contract prices. Fayek (1998) suggests that qualitative factors, such as the expertise of the contractor for the construction to be done, and the relationship between the contractor and the agency issuing the contract also affect construction costs. As the purpose of this study is to identify the different factors that need to be input in a GIS model to make a performance indicator that allows a comparison between different alternatives, understanding the relationship of different factors to the cost would need to be considered.

Building a utility index based on cost has been widely researched. Evaluation of bridge improvement projects for bridge management, which includes both cost of construction and maintenance cost, is discussed by Sobanjo (1991). The benefit index is based on an established list of criteria that includes traffic volume, improvement in structural capacity, clearance, etc.

Computing a ratio of the benefit index to the project cost is a realistic and effective way of evaluating each feasible strategy. Life-cycle cost analysis can be utilized to compute net benefits and to compare between different alternatives. Cost estimates will have uncertainties, which could be computed in a probabilistic method. A deterioration model can be applied to reflect the timing of the required maintenance (Golabi et al., 1993) indicating a probabilistic estimate. The model represented by Golabi et al. (1993) considers Markov Chain deterioration model and the dynamic programming optimization theory.

Another analysis technique for cost is using fuzzy sets. Sobanjo (1999) represented an economic evaluation of buildings, a technique that can also be used for transportation construction. An algorithm can be formulated for life-cycle cost analysis by using fuzzy numbers to represent the variables. Fuzzy sets theory has been proven as a valuable tool for handling uncertainties due to subjective estimates in decision-making models.

2.5 Evaluating Time Factor in Construction

Time is an important factor in decision-making for roads construction projects. During construction, many inconveniences occur in terms of traffic delay. Also, trying to solve traffic problems as quick as possible is always a high advantage. However, when time is faced, there are always constraints on how to optimize time, cost, and quality of the construction done. In general, it is possible to say that time and cost are inverse proportional to each other.

There are different contracting methods applied to analyze cost vs. time in roads construction. Herbsman (1995) and El-Rayes (2001) have discussed the method of bidding on cost/time, such as the A+B method, to encourage competition among contractors to minimize project duration. Another method is to have contractual clauses that provide financial incentives or disincentives to reduce construction duration have been discussed by Jareidi et al. (1995). Some large projects, especially those that significantly disrupt traffic, use night-time construction to cut construction time by requiring contractors to work off-peak hours (Ellis and Amos 1996; El-Rayes and Hyari 2002, 2004).

When duration is reduced, there are fears that the quality of the construction work would not be maintained at high standards. However, as insurance, there are different contractual methods that allow that. Contractual warranty clauses are included to improve quality by making contractors liable of the performance of the facility after project completion (Anderson and Russell 2001; ENR 2002). Another method is a multi-parameter contract that provides incentives to contractors to improve quality performance (Anderson and Russell 2001).

Considerable literature is available in models for optimizing construction resource utilization by various methods, including genetic algorithms (GA), linear programming, integer programming, and dynamic programming. There are models which objective is to minimize project time and/or improve resource utilization (Easa 1989a; Chan et al. 1996; Hegazy 1999; Gomar et al. 2002). Other models have the objective to minimize time and cost for non-repetitive construction using time-cost

trade-off analysis (Burns et al. 1996; Feng et al. 1997; Li and Love 1997; Maxwell et al. 1998; Li et al. 1999; Feng et al. 2000). A different model is also utilized with the objective to minimize time and/or cost for repetitive construction (Moselhi and El-Rayes 1993; Senouci and Eldin 1996; Adeli and Karim 1997; El-Rayes 2001; El-Rayes and Moselhi 2001; Hegazy and Ersahin 2001; Hegazy and Wassef 2001; Leu and Hwang 2001).

Although there are extensive literature available on optimizing construction resource utilization, there is little research available on multi-objective models for optimizing time, cost, and quality.

Quantifying quality performance can be at high importance as the time duration of roads construction. Quality performance indicators have been determined in studies to develop quality-based contractor prequalification systems (Anderson and Russell 2001; Minchin and Smith 2001). Genetic algorithms in optimizing time, cost, and quality have been discussed by Goldberg (1989). The purpose is generating populations of solutions with parameters passed down from the parent population to the child population. A combined population of both the parent and child is made to compare solutions in the child population with the initial solutions form the parent population. The best solutions in this combined population are then passed down to further generations until an optimal solution is found (Deb 2001; Deb et al. 2001; Zitzler et al. 2001). This study will further investigate in a method that can be utilized by the GIS model for comparison between different alternatives of roads construction considering the factors of time, cost, and quality.

2.6 Decision Path for 'Big Dig' Project in Boston

In 1982, planning for Big Dig officially started aiming to reduce congested traffic in downtown Boston and relieving traffic flow to and from Logan Airport. In 1983, an environmental impact study of proposed mega-project was made. By 1985, the project was estimated at $2.5B. Funding for the project was requested from Congress. In 1987, a public works bill was passed by US Congress appropriating funding to the project. President Ronald Reagan vetoed the bill based on the extravagant expenses attached to the project. However, US Congress overrode the veto and ground first broke in 1991 marking the beginning of the execution of the project, 9 years after it was originally planned.

During execution of the project, many problems arose. From those problems, necessary data, which would otherwise be though as insignificant, is gathered to be included in the model for this study. Downtown Boston through which the tunnels were to be dug is largely a landfill area. Therefore, geological data of the area is necessary to be included n the GIS model. The area included existing subway lines as well as numerous utilities pipes and cables. Thus, utilities data of the infrastructure is also necessary to be included in the GIS model. However, there are uncertainties encountered which are necessary to include in the model. There were unexpected archaeological barriers encountered, glacial debris, buried houses, and sunken ships lying within the reclaimed land. Those uncertainties and others would not be initially known. Therefore, in the model, a variable for uncertainty is necessary for inclusion in the equation. It will be further discussed later in the following chapters.

Some environmental and health obstacles were also encountered. During excavation, several underground toxins were released. This caused an environmental health concern. More funding was required to reconcile the problems, which also caused in further delays in the project. Also, as this mega-project is largely underground, the homes of millions of rats were disrupted forcing them to roam the streets of Boston in search for new homes. That as well caused a major health concern which had to be remedied. More funding and further delays were caused. Those surprises need not to be surprises as they must have been known during the environmental impact study of the planning phase. Thence, it is of great importance to incorporate environmental data that includes the flora and fauna of the project area.

In 1994, when federal environmental clearances it was already 9 years since 1985, when the budget was first estimated. Therefore, naturally, inflation has already added into the budget. With stricter regulations from the regulatory boards, more funding is now also required to be in accordance to all regulations. This signifies that when a budget is estimated, it should not be according to current cost, but expected future cost. The future cost is not simply calculated due to inflation with an expected interest rate, but should also incorporate costs of mitigation to abide by new regulations.

Professional liability insurance coverage of the Big Dig project was poorly managed (Sullivan 2005). In December 2000, a report from the Office of the Inspector General was critical of the poorly managed and

ineffective cost recovery program through litigation. The report included that the program was only able to recover $30,000 from more than $80M in claims. In 2003, cost recovery for the Big Dig was greatly pursued and in two years recovered approximately $4M, while millions more were still being sought.

Several contractual problems arose during the project. Hence, cost recovery process needs to rely upon professional liability insurance claims filed against designers and construction manager. The Architects/Engineers Professional Network defines professional liability as follows:

> "Professional Liability Insurance also known as Errors and Omissions, or Malpractice insurance. This insurance provides coverage to defend and indemnify the design professional against claims alleging negligent acts, errors, or omissions in the performance of the professional services (wrongful acts). Wrongful Acts are not limited to defects in plans and specifications. Coverage usually extends broadly to encompass most of the professional services rendered by A/E (Architectural and Engineering) firms. The policy will pay on behalf of the design professional those damages that the design professional is legally obligated to pay as a result of a wrongful act."

The main reason behind this type of insurance is twofold:

1. To determine if the taxpayers received the protection they paid for.
2. To determine if the design firms and construction manager complied with their contract requirement to maintain a certain level of insurance coverage.

In May 1995, the Massachusetts Highway Department created the Owner Controlled Insurance Policy program, which included professional liability coverage for the design firms. This coverage was paid for through a cost sharing formula called the "Professional Liability Wrap-Up Insurance Premium." The liability aggregate was set at $35M with the premium for the first $30M in coverage being paid for with taxpayers' money. The premium cost for the remaining $5M was to be shared by Bechtel/parsons Brinckerhoff and by the designers in proportion to their total design fees.

The design contracts that pre-dated the Owner Controlled Insurance Policy were not covered by the Policy. Instead, the Big Dig required contract specific policies with specific insurance coverage as recommended by Bechtel/Parsons Brinckerhoff. These contract specific policies were paid for by the taxpayers as well. The designers were reimbursed for insurance premium paid as a direct expense for each contract.

Understanding from this finding that any firm whose insurance costs are reimbursed by the government authority should be required to provide any insurance information upon request. Proper record-keeping is critical to protect the government's investment. Therefore in the GIS model, it is also an extra to include a GIS-based construction management system to manage all data including that of insurance.

A risk assessment measurement tool is a necessity to determine the amount of professional liability coverage needed on a contract. Coverage should, therefore, be reviewed based on risk assessment.

2.7 Reconstruction of Interchanges in Dubai

In the early 1990s, the city of Dubai decides to convert a main arterial road to a freeway system, which would be the first time in the history of the city. Dubai – Abu Dhabi road was chosen to be the first road to be converted to a freeway system. The old intersections were planned to be converted to interchanges.

As designs of the interchanges were made, they were first designed such that the interchanges can hold high capacity of traffic. However, planners at the time found those designs to be too expensive and unnecessary as traffic was anticipated to be lower than the capacity to be provided. Thus, the designs have changed to smaller interchanges.

After construction of the road interchanges, it has been found that some of the interchanges have not been adequate as they link the highway with industrial areas and the interchange was very small to uphold the capacity of trucks.

In the late 1990s, there was a population boom, which later increased even further in the early 2000s. The economic boom resulted in large real-estate projects that the highway started to serve new communities that are residential, commercial, and industrial. Within 10 – 15 years of the construction of those interchanges, plans were immediately made to

re-construct the interchanges. Looking at how decisions are made within the context of decision theory, it is understood that the cost was a major factor for the initial decision. Later, it has been apparent that the economy of the city is directly affected by the transportation network it has, which is completely congested. Thus, it was negatively affecting the economy. Thus, in the late 1990s, plans were immediately made to re-construct the interchanges. Now, there is an added cost for demolishing the old interchanges and building the new ones in its place. Besides that, there is also a regret factor for deciding to go for a much smaller interchange earlier.

In the initial stages, there were three different design alternatives for decision-makers to choose. One of those alternatives was the design they actually built the interchanges in the beginning, and the latter design, which exists today after re-construction, was also evaluated at the time. A thorough example using the regret model proposed in this study is illustrated in Chapter 4 to show how the regret model would have been applied and anticipated the results.

All of those factors will be taken into account in this study to understand further how a GIS model can help in identifying best traffic engineering alternatives in road construction. What this case study helps in the research is that it emphasizes the importance of uncertainty. The planners have not anticipated an economic boom that would result in a population boom that would naturally result in the requirement of more traffic capacity. Due to this uncertainty, it has added more cost for demolishing old interchanges to build the new ones, created more delay

before and during construction, and also created a regret factor to the civil body that took the decisions.

Since population growth, economic boom, and urban expansion was unprecedented within a very short period of time, this study looks into the socio-economic data required within GIS and how extrapolation of data is necessary to minimize the consequences of uncertainties when developing an index to evaluate different road construction alternatives. Understanding traffic impact assessment is crucial to develop the GIS model.

2.8 Construction of Highway around Plzeň

Building a highway bypass in Plzeň had two main alternatives, (K) and (S). (K) branched into two variants (KU) and (KUO) as it was adjusted due to compromises throughout the controversy. (S) branched into two variants of (SU), (SUK1) and (SUK2) as it was also adjusted due to compromises throughout the controversy period. Those variants are illustrated in Figure 2.1.

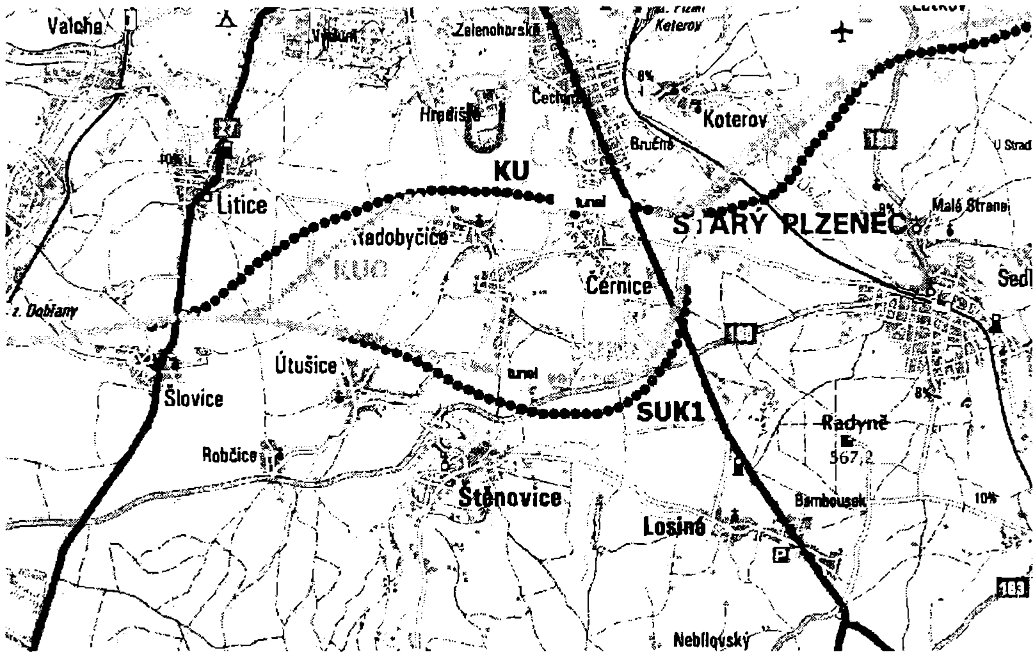

Figure 2.1 ALTERNATIVES OF HIGHWAY BYPASS IN PLZEŇ, CZECH REPUBLIC

In 1991, alternative (K) was suggested by experts and approved by Czech Government, and though with some objections, even the municipality of Plzeň. The alternative was to pass through in between villages Bručná and Černice. The inhabitants of those two villages have loudly protested and requested revocation of the decision.

The municipal government of Plzeň and the developer started to promote an alternative variant (S). This route would be further to the south from Plzeň going around, or alternatively, through the hill Valík, rather close to two small villages Štěnovice and Útušice. Inhabitants of those two villages have protested the decision.

In 1991, the newly formed Czech Government recommended another complex assessment of the two alternatives (SU and KU). It had the form of environment impact assessment (EIA). Its final report recommended a further modification of (SU) to brink in the variants of (SUK). In 1993, Czech Government requested an EIA for both alternatives. Experts recommended variant (S). In May 1994, the Government repeals previously approved alternative (K) and approves a new resolution, changing the corridor for the Plzeň bypass in favour of the (S) variant. Throughout the controversy, alternative (S) has been under construction on an on/off basis due to legal battles.

In 1996 and 1997, construction permits for two highway bridges on regional rivers were approved. The bridges were to be built no matter whether alternatives (K) or (S) are decided. The bridges were completed in 1998. They dominated the landscape as it did not connect any highway at either ends. The curvature of the bridges were aligned to suit alternative (S) more, making it more expensive to re-align alternative (K) to suit the bridges. Supporters of alternative (S) used propaganda by marketing the new bridges. People now became familiar with the shape and curvature of the future highway.

Constitutional complaints, appeals, and judicial lawsuits against the decision followed. Due to a court decision from 1997, a new EIA procedure started in 1998. The court decision was due to the fact that the 1993 EIA was the first EIA for a highway nationwide and one of the first ever, and that it was not according to legal procedures. Geological condition for a planned tunnel through the hill Valik for alternative (S)

was not fully explored during the 1993 EIA. The 1998 EIA found it to be a predicament. Thus, it is understood from such decisions that geological data is necessary to have within the GIS model that this research discusses. The new EIA recommended alternative (K). However, work on (SUK) went on. Environmental activists and concerned villagers appealed again, but unsuccessfully. In 2001, the Supreme Court confirmed the legality of (SUK).

Interpreting how the decision was made is complex. It appears to be a struggle between environmental activists and non-transparent coalitions of local politicians, businessmen, and developers. However the controversy also included a pool of experts. Initially, experts recommended alternative (S). As experts gained more experience they were indecisive for the best alternative. At later stages, with more experience, and more scientific findings, experts recommended alternative (K) as it was cheaper due to being shorter, with better traffic flow due to reduced travel time, and less impacting to the environment.

In 1999, housing permits were issued along the alternative (K) corridor. The permits were legally issued, since the new corridor for alternative (S) was approved and the government repealed the corridor for alternative (K) in 1994. With the bridges built according to the curvatures that favoured alternative (S), and as houses have been built along alternative (K) corridor, alternative (S) has become irreversible.

In 2001, traffic conditions in the city of Plzeň have become unbearable. Due to the traffic congestion, health risks have also become severe for

the air quality of the city. A new decisive factor has been raised, **time**. It has become apparent that it does not matter whether alternatives (K) or (S) were best, but the new question for a final decision was, "which alternative will be completed **sooner**?" Since alternative (S) was partially built since 1994 and the bridges were already more aligned for alternative (S), the final decision was clear.

There are many factors that influenced in the decision-making of this case study. The study will look into different GIS data needed, such as geological and environmental data that is essential for the decision path, it also looks on how time can dominate decisions as one of the major factors in roads construction, sustainability/time. The study focuses on how the availability and reliability of data is important in understanding the effect that regret is involved in the evaluation of alternative road designs.

2.9 Construction of Dublin Port Tunnel

In 1990, there were high congestion in city streets due to Heavy Goods Vehicles (HGVs) leaving Dublin Port and traveling through the adjacent downtown city streets. Two alternatives were presented, i) move Dublin Port, or ii) build a tunnel to divert HGV traffic away from city streets.

In 1991, a study shows that building a tunnel is unreasonable due to the following facts, i) the tunnel was to be a toll road, and ii) the tunnel is lengthy, both of which were found to be inconvenient since HGVs would not take a lengthy route and pay the associated tolls. There are different reasons for the Port Tunnel:

- Reduce traffic congestion from city streets.
- Improve air quality.
- Ease of port transportation to be internationally competitive.
- Increase value of lands where Dublin Port is situated to maximize the potential benefit to private developers.

Since the last reasoning was not to the benefit of moving Dublin Port, a Port Tunnel project has been approved.

There were many controversies that surrounded Dublin Port Tunnel project.

- House Damage
    - Vibrations due to hard-rock boring caused some damages to nearby homes. 241 claims have been filed so far. This shows the necessity of different GIS data for the model discussed in this research, which includes geological data, housing data, and cadastral data.
    - Decision: €1.5M set aside for compensations.
- City Center Ban
    - A ban will be made effective on all HGV vehicles from using City Streets from 7am – 7pm. Thus, forcing HGV vehicles to use the Port Tunnel, and therefore pay a toll each way.
    - Decision: No toll will be levied from HGV vehicles to use the tunnel.
- Height Problem
    - The maximum height of vehicles allowed through the tunnel is 4.65m instead of the standard 5.5m. Though

majority of HGVs can go through, this still causes a problem to higher vehicles.

  - Decision: Although this problem was realized early during construction, no action was made to rectify the problem due to the fact that majority of HGVs are not higher than 4.65m. However, it might cause an inconvenience. If the inconvenience of the height problem will outweigh the cost of rectifying the problem at the time it was recognized, then it might create a controversial decision-making problem. The study will look into the validity of this statement to generalize rules to all roads construction projects when computing a performance index wile evaluating alternatives. Regret is influenced by how a decision could or could not be changed both in the long and short terms.

- Water Leaks
  - Similar to problems faced in Big Dig project in Boston.
- Cost Overruns
  - As many mega-projects, this problem is always a disease. The project was estimated at €450M for construction and €302M for land acquisition, design, insurance, legal and other services, and supervision by a construction project management firm. Therefore, total cost is €752M.
  - In 2005, the main contractor launched a claim for an additional €300M due to construction problems, which Dublin City Council is yet to approve. Though going over the budget is not as appalling as Big Dig project, it still is an issue.

The study will go over the decisive factors that chose Dublin Port Tunnel over moving Dublin Port. The study will also consider the uncertainties that carried hefty consequences for this decision to better understand the type of GIS data required for the proposed model.

3. GIS Model for Road Construction Design Alternative Analysis

3.1 Introduction

The quality of a decision depends on the quality of alternatives and the ability to develop a detailed analysis for selection. However, as in any analysis, an analysis is only as good as the data inputs. If the data is not accurate or insufficient, the analysis will therefore be similarly inaccurate. When working with data, it is important to consider the macro-level and micro-level data for the selection analysis. In this chapter, the GIS data that is necessary to make a decision model that is able to select between alternatives is introduced. Not only is it important to look at the accuracy of the data, but also its completion. Sometimes, when looking at different alternatives, some details that might change the outcome of the whole construction process are ignored. For example, when neglecting the fact that Boston is on a landfill, unexpected shipwrecks were discovered buried under the city during excavation of the Big Dig project tunnels. Hence, sometimes it is not only the quality of the data that is only important, but also considering the completion of this data.

Decision makers would regret an unexpected outcome. Thence, it is important to consider the different types of attribute data to understand the multi-criteria nature of the analysis. An analysis with diverse variables opens the door to more propagated error and therefore, less accurate results. Understanding a GIS model for analyzing different road

design alternatives allows the permeation of potential causes of regret. In this chapter, an overview of the different GIS model and data are addressed that would be useful when comparing two or more road design alternatives.

The process for evaluating alternatives starts by proposing an action. Then, it is necessary to define the objective of such an action, as in what is the purpose. Then to develop different alternatives, which are considered reasonable and meet the objective. The alternatives are then evaluated from a macro-level point of view, which include the planning and environmental models. This analysis will eliminate some of the alternatives. The remaining possible candidates are then analyzed in the micro-level, which include a full traffic study. Finally, the alternatives are given a score each according to the criteria and the weight given for each of the major factors.

In this chapter, different models for each criterion are introduced along with the different types of data that is usually input into a GIS for analysis purposes. The different data and models allow the understanding of the complexity of a multi-criteria decision. This complexity is directly reflected upon the different doors where error can enter, and therefore, affect the confidence level of the input data in a model. This entails the risks penetrating the models, and hence, regret may be born for the decision made due to the available data. In the next chapter, regret is discussed in further details and how the performance indicator from various criteria coming from different models each, are input into the analysis process of the regret factor.

The different aspects of a GIS integrated data for roads construction alternatives in the scope of this study are portrayed in Figure 3.1.

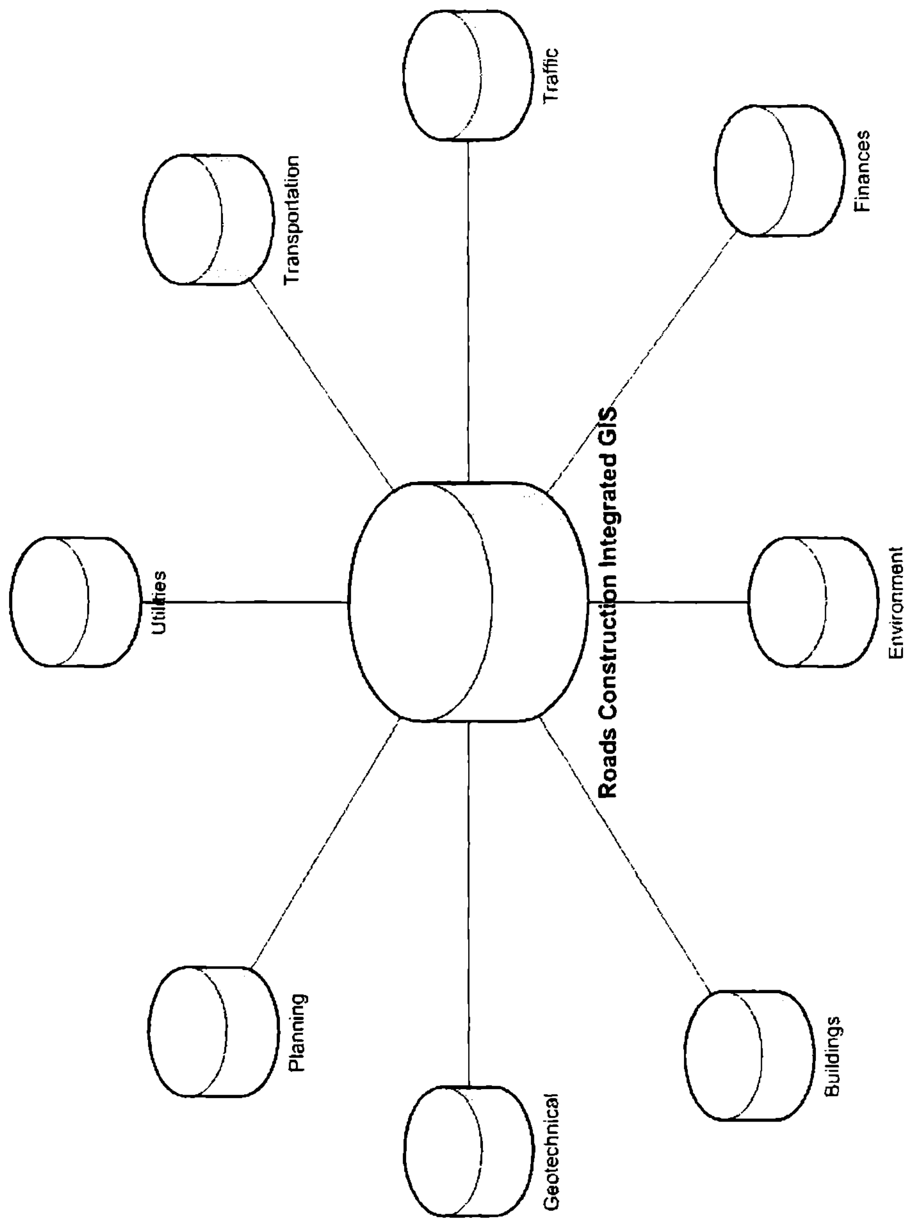

Figure 3.1 INTEGRATION OF GIS DATA FOR ROADS CONSTRUCTION ALTERNATIVES

Within GIS, a master database is created linking all other databases as follows:

1. Master GIS
    a. Traffic
    b. Transportation
    c. Utilities
    d. Planning
    e. Geotechnical
    f. Buildings
    g. Environment
    h. Finances

The stage at which the regret model is applied starts as soon as different design alternatives for roads construction are defined. Once the alternatives have been defined, the regret model, as proposed in this study, is applied to determine the score ranking of each alternative based on regret. This business flow is illustrated in Figure 3.2.

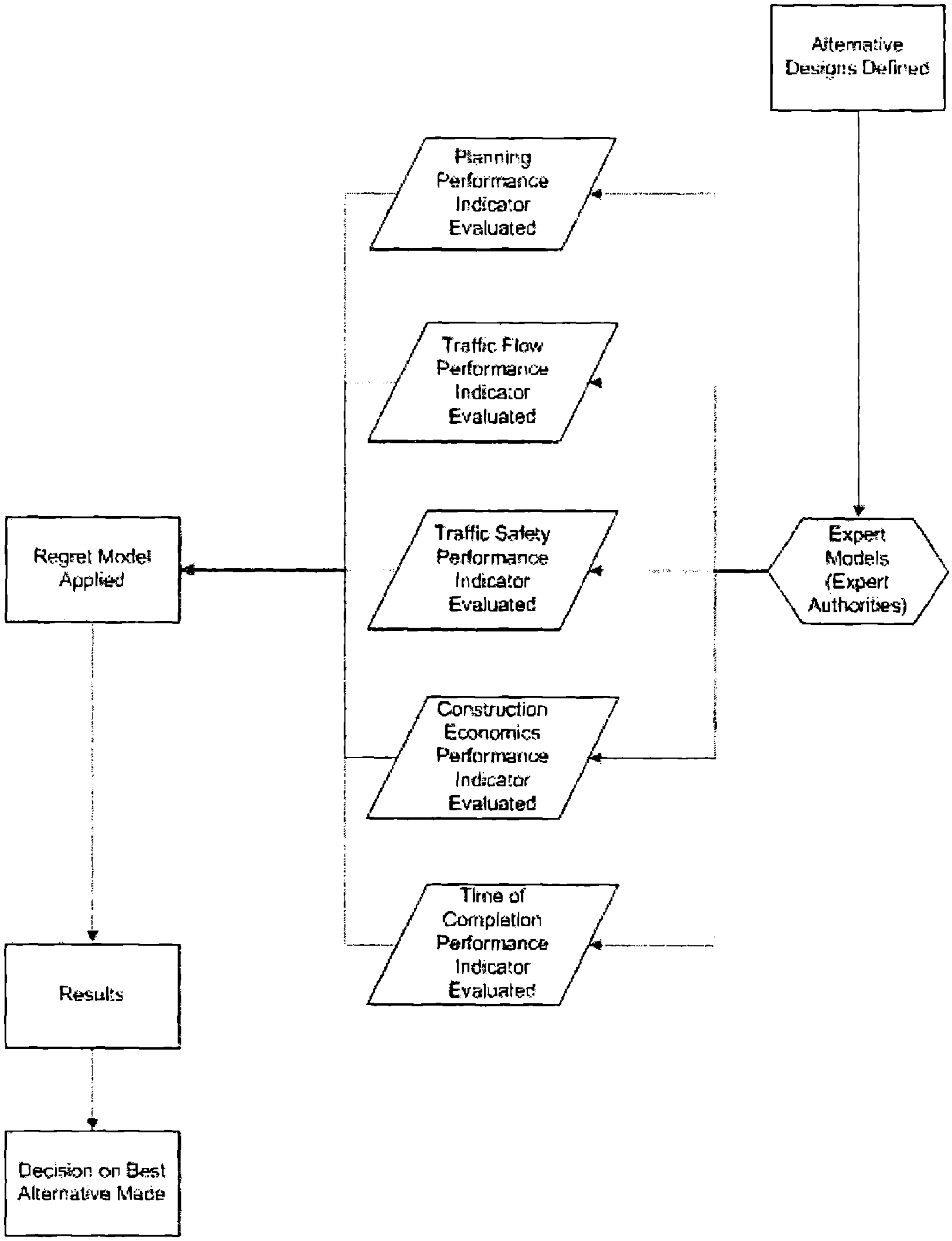

Figure 3.2 MODEL APPLICATION FLOWCHART

When designing roads, there are different types of performance indicators which include i) driver behaviour, ii) road behaviour, iii) environment behaviour, and iv) vehicle behaviour. For the purpose of this study, driver behaviour is not a controlled factor and therefore assumed not part of the performance indicators that would allow the comparison between different road construction designs. It is assumed that drivers would behave in a similar fashion when comparing different alternatives. Similarly, vehicle behaviour is an independent variable of the road construction design as well. Nevertheless, environment behaviour may be a comparative factor. For example, theoretically, if a road is covered, then rain and snow can be eliminated as an environmentally potential hazard to traffic. Such a design can be compared to the safety factors of other road geometries. However, it can be argued whether or not such a design constitutes as environment behaviour or road behaviour. Road behaviour is mainly defined as geometry, traffic flow, and safety of the road design.

Evaluating the performance indicator in terms of traffic constitutes the following factors:

a. Evaluating, simulating, and optimizing the operations of traffic flow and transportation systems.
b. Modelling existing conditions and predicting traffic flow behaviour of the different alternatives of the new proposed design.
c. Evaluating planning, design, operations, and construction projects that comprise additional factors.

The GIS model to evaluate the best roads construction alternative starts at different phases as follows:

a. Planning
b. Traffic

3.2 Planning Data Considerations

The central element of a planning support system is geographic information systems (GIS) (O'Looney 2000).

The model starts with a planning analysis tool to evaluate the planning aspect of the road construction alternative. This phase starts with a generic planning analysis. The planning phase determines the travel demand model, which is essential in the evaluation of different road alternatives, for the better understanding of the required capacity and general traffic flow model that the demand creates. The GIS inputs to the planning model are shown in Figure 3.4. The GIS model needs to contain different planning data that include the following:

a. Administrative Boundaries
b. Subdivisions
c. Zoning
d. Land Use
e. Parcels
f. Parcel Valuation (Value Assessment)
g. Right of Way

h. Utilities Corridor
i. Structure Conditions (Building Inspection)
j. Infrastructure Condition and Capacity
k. Transportation Systems
l. Hazard Locations (Emergency Management)
m. Accidents and Crime (Public Safety)
n. Land Conservation
o. Historical site
p. Demographics
q. Buildings
r. Facilities

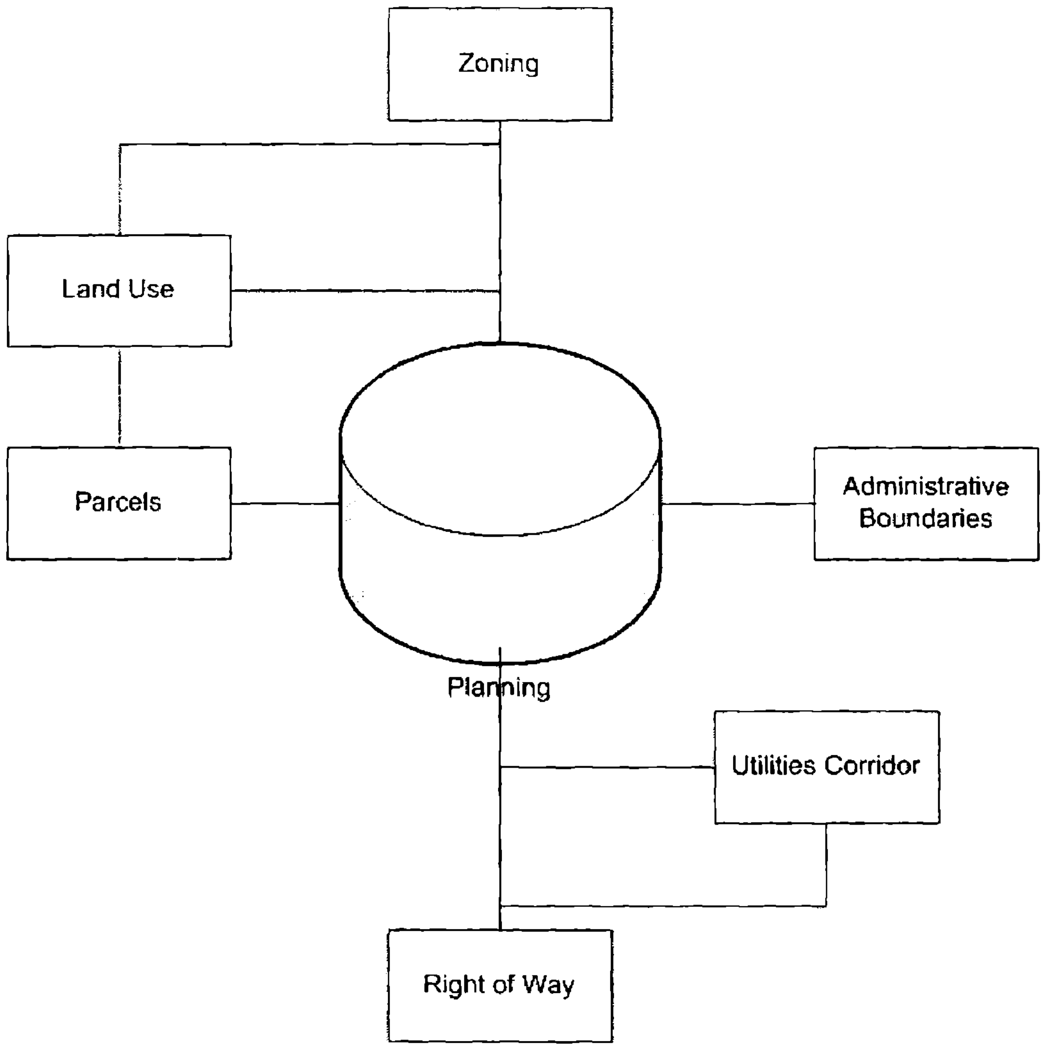

Figure 3.3 GIS INPUTS FOR THE PLANNING MODEL

The outcome of the Planning Model paves the way to the Travel Demand Model. The travel demand model determines traffic generators. A prediction model for the travel demand is based from the planning data to understand origin and destination. Once the origin and destination is determined, the travel demand model represents the mode choice, time-of-day travel, and route choice.

The travel demand model is the outcome of the planning model to compare between different roads construction alternatives. Nevertheless, the GIS model should not be completely relying on travel demand models as it has not been designed for day-to-day operations of traffic flow. For that Intelligent Transportation Systems are in use. Hence, it is imperative to consider the use of ITS as part of the Traffic Model and not Travel Demand.

Administrative boundaries are intuitively used in the GIS data model to understand the jurisdictions, especially if the finances are being shared over several jurisdictions.

Zoning data is very important to understand the density planned in the area. From zoning and land use, traffic generators are determined. From land parcel data, the areas of plots to determine the expected population density as proposed by land use and zoning data are understood. This data is important for the GIS to understand the travel demand model.

Right of way data and utilities corridor also determines the maximum width of road to understand the maximum capacity of the road network.

Also, it is imperative to verify whether land acquisition for different roads alternatives are necessary. If so, the cost of compensation can be determined from parcels data. Once the planning phase is complete, the traffic model is run.

The inputs for planning data model in GIS include the following:

- Values
  a. Environment
     i. Environmental Protection
        - This data is used to establish a weight for environmental impact in the analysis.
  b. Equity
     i. Social equity values, such as improvement of conditions in communities with low-income. It is the basis of how distribution of resources, services, and opportunities within the city.
        - This provides data in the GIS on which networks are considered higher priority than others.
  c. Economy
     i. Viewing land as a commodity for the production, consumption, and distribution of products and services for profit.
        - This provides data in the GIS for the value of the land as unity of currency.
  d. Liveability

i. Social reactions on planning changes. This includes terms such as "not in my back yard" (NIMBY). This can alter political changes in any community, and therefore as important in decision-making as other factors.
   - This provides data in the GIS for quantification of risk and regret factors.

The values in place would subject decision-makers to consider three primary contradictions, as seen in Fig. 3.4, in which an optimal solution is required.

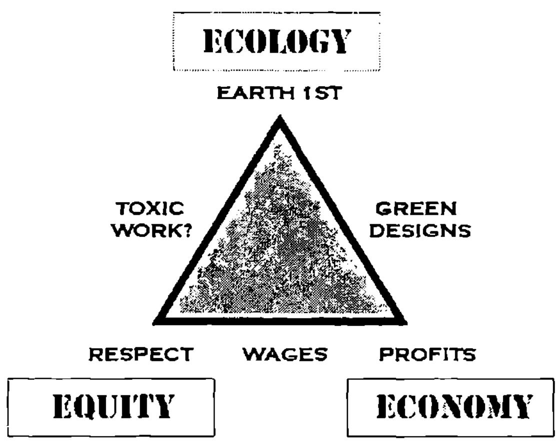

Figure 3.4 PRIMARY CONTRADCTIONS IN A PLANNING MODEL

e. Planning Support Systems
   i. Population / Economy
   ii. Environment
   iii. Land Use
   iv. Transportation / Infrastructure
   v. Community Report

f. Network of Plans
    i. Area-wide Policy
    ii. Mapping administrative boundaries and general policies
    iii. Conservation
    iv. Rural
    v. Urban
    vi. Community-wide Design
    vii. Specific spatial organization of land uses
    viii. Location
    ix. Type
    x. Mix
    xi. Density
    xii. Small Area
    xiii. Urban areas within a community
    xiv. Transportation corridors
    xv. CBDs
    xvi. Neighbourhoods
    xvii. Development Management
    xviii. Program of action for development plan
    xix. Period of plan
    xx. Quality / standard of living

g. Sustainable Community
    i. Environment

In planning models, just as it is in economic models, supply and demand are essential parts of evaluation of land value and usability of land for

transportation developments. Hence, GIS data is divided into categories that determine supply and demand of land and how they are regulated. It is to be noted that the transportation infrastructure contributes to the supply of necessary services as it can be shown in Fig. 3.5. However, since transportation facilities uses lands that could have otherwise been developed, it takes away from the supply of land, as can be seen in the infrastructure deductions to land use capacity analysis in Fig. 3.6.

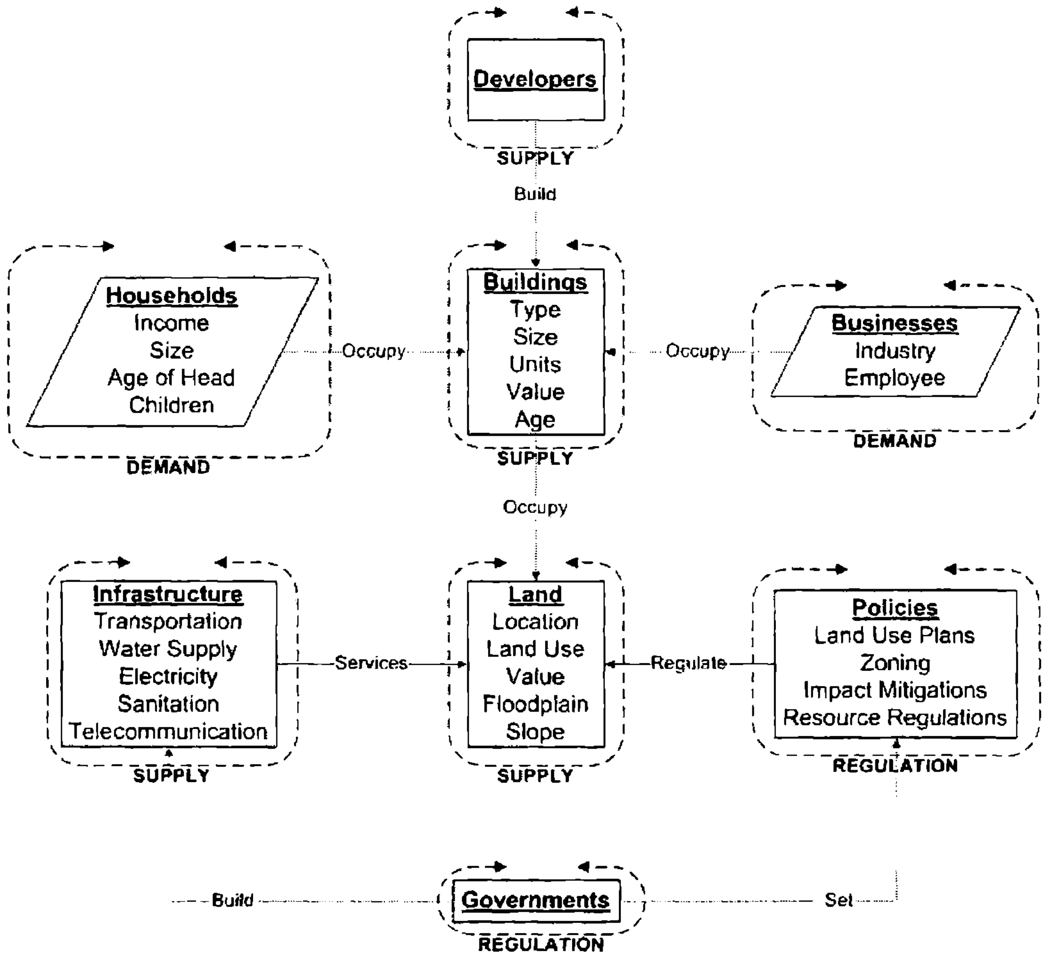

Figure 3.5 GIS DATA MODEL FOR PLANNING SUPPLY AND DEMAND

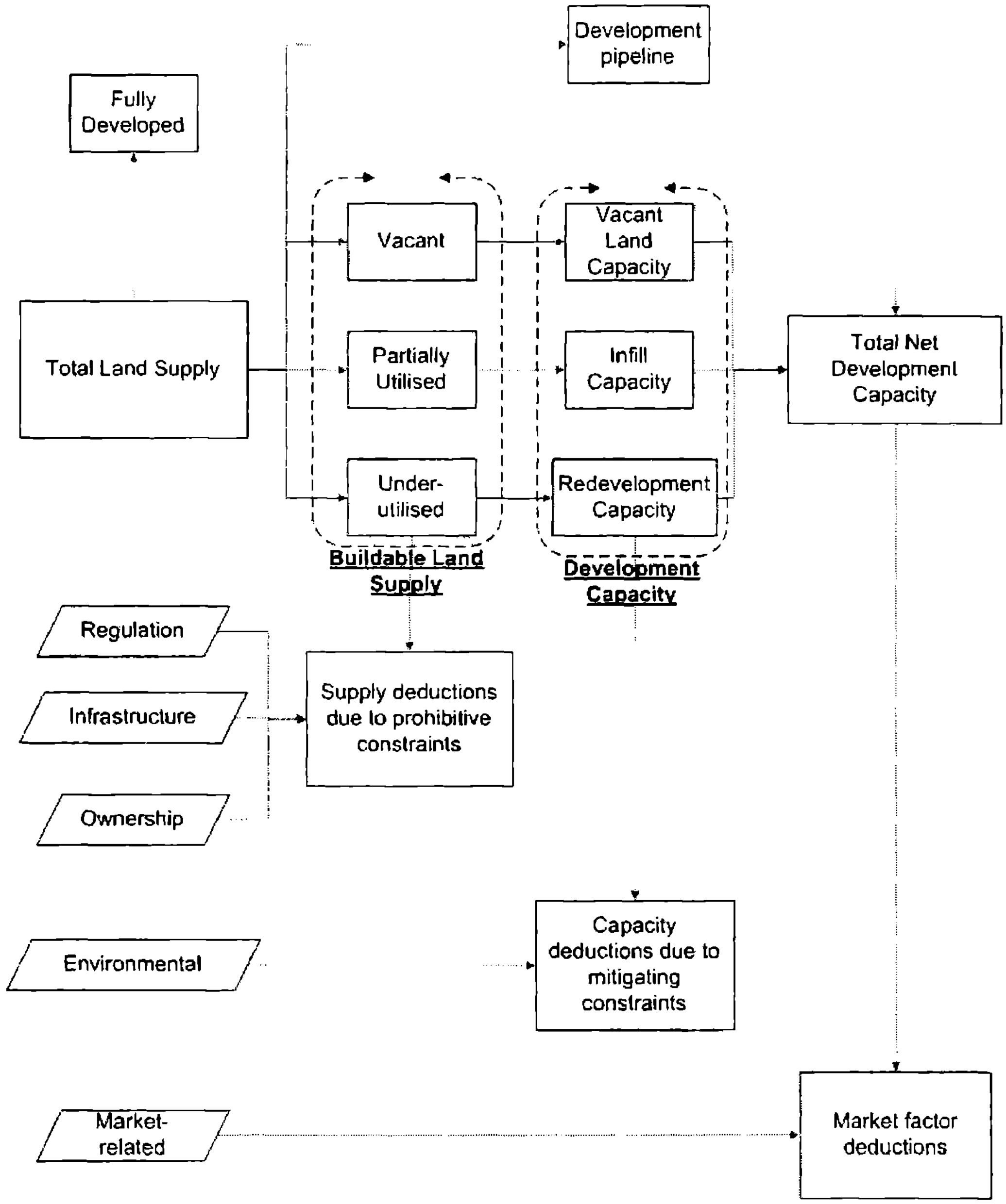

Figure 3.6 LAND USE CAPACITY ANALYSIS (Moudon and Hubner, 2000)

3.3 Traffic Analytical Considerations

An analytical model is necessary for traffic to analyze traffic flow and operations. The Highway Capacity Model (HCM) may be used while other uses of simulators may also be possible.

When identifying planning areas for developments, it is necessarily important to consider the appropriate width of the right of way that is essential to use. Within the GIS model in this study, when considering different alternatives for roads construction, it is important to note the importance of the percentage of use of the road to the right of way. The smaller the width of the right of way, the more land can be developed. However, there is an inverse proportional relationship between the width of right of way and the development of land. Although the smaller the width of the right of way means that there is more land to develop, the more land to develop means that there is a higher density that would require extra transportation infrastructure and utility services, which would mean a bigger right of way is necessary. This point, for purposes of analysis, would be called the equilibrium point between the demand for the width of the right of way and the supply necessary to meet such a demand.

The transportation infrastructure is directly related to this phenomenon, and therefore, it affects the performance indicator of the planning, which is reflects the impact of the economy and environment, and traffic flow. It is important to consider long-term impact of the roads construction alternative according to the assumed life cycle of the road. However, the

right of way may be reserved well in advance to allow future expansion of the road and utilities networks, if necessary. This is especially important in developing areas. Also, risks such as newer technologies that might require future utility services to be laid by the right of way. For example, in the past century, telecommunication networks were first laid for copper cables and then later fiber optics were used within the corridor. Despite the fact that newer technologies are heading towards wireless telecommunications, for transportation networks, it might be necessary that a light rail or other mass transit system might require additional right of way.

For the purpose of this study, a comparison is done between different alternatives using various traffic flow conditions based on the criteria. This may include optimization of traffic signals through optimized phase timings, capacity analysis, split optimization, coordination plans, and others.

Three stages of traffic simulations would be run to evaluate the traffic flow, macroscopic, mesoscopic, and microscopic simulations are run.

A macroscopic simulation is based on deterministic relationships of flow, speed, and density of traffic on sections of roads in a network. During analysis, if a roads alternative fails at this stage, then it is removed from the list of feasible alternatives. Since macroscopic models do not require so much computer requirements, it would be useful to have this simulation run to identify feasible roads alternative before further analysis is made.

A mesoscopic model is a hybrid of both a macroscopic and a microscopic simulation. Although the unit of traffic flow is an individual vehicle just like a microscopic simulation, the vehicle's movements are managed by the average speed on the travel link. The simulation takes place on an aggregate level and does not consider dynamic speed and volume relationships.

The final simulation stage considers a microscopic simulation is used to have a higher accuracy of the traffic flow model. This simulation is based on car-following and lane-changing theories. During entry of the vehicle in the simulation, a destination is assigned to it. Since planning data, which includes zoning and land use, the traffic generators are already established and the destinations assigned to each entering vehicle are therefore based on the planning data. However, such a simulation usually requires extensive computer operations.

According to planners, it is agreed that travel is derived from the need to reach particular destinations and not the trip itself. Therefore, it is believed that the objective of any transportation system is to ease the ability to reach destinations, which is counter to the concept that the objective is to relieve traffic congestion (Handy and Niemeier 1997; Levine and Garb 2002; Miller 1999).

A decision support system, as in a GIS model, two categories for transportation performance are used, mobility and accessibility. Mobility determines the traffic flow factors on the transportation network while

accessibility connotes the ease of reaching destinations (Altshuler and Rosenbloom 1977).

Since this study focuses on the determination of the best road construction alternative, the viewpoint is both from a planning perspective, which focuses on accessibility, and an engineering perspective, which focuses on mobility. Each of those main categories would have different weights that are defined by the decision-maker (user).

Accessibility is best improved by bringing origins and destinations closer to each other. However, since this research is mainly focused on the best road construction alternative, it is already assumed that origins and destinations have already been pre-determined and based on the given data, how mobility is affected by different alternatives by determining traffic performance indicators.

As new roadway networks may trigger the growth of developments along the corridor, a reverse benefit may be assessed to a planning perspective for accessibility issues. For example, a road with high capacity would allow for greater developments along its corridor, especially if the mobility along the road is high. On the other hand, a road with less capacity can become a detriment to any future growth due to constraints on mobility.

To best portray this is in an example. It can be imagined that a road network with two alternatives are in question. One of which would give a

capacity of 16,000 vph while being LOS B. The other would have the capacity of 8,000 vph, and for purposes of this example, would also have a LOS B. It is obvious that the road alternative that provides higher capacity is more expensive. However, from a planning point of view, the growth of developments along the corridor of the road is higher with the highway of larger capacity. That might change the land value and value to the economy due to the increased potential development along the corridor. Yet, inversely, with a higher capacity road network, there is a higher environmental impact, which would result in mitigation costs. It is therefore not a simple equation that needs to be balanced and optimized, but a more complex formula to understand how the best decision is to be taken.

3.4 Traffic Data Considerations

Simulations and HCM methods vary on the type of measures used for traffic performance in terms of time of analysis. Nevertheless, a consensus is established for the type of measures, which include density, speed, and delay.

For the GIS model to evaluate density, the average spacing between vehicles is evaluated. From the road geometry and number of traffic, using a microsimulation, the density of traffic can be spatially analyzed.

In general, the performance measures include traffic safety, such as crashes, and cost of property damage, injuries, and fatalities. Also, efficiency of traffic is evaluated based on throughput, volumes, vehicles-miles (vehicle-kilometres) of travel (VMT), mobility, such as travel time,

speed, vehicle-hours of travel (VHT), productivity (cost-savings), and environmental measures such as emissions, fuel consumption, and noise.

The following data is necessary in the GIS model:

1. Geographical scope
    a. Isolated location
    b. Segment
    c. Corridor
    d. Region

2. Facility type
    a. Isolated intersection
        i. Single crossing point between two or more road facilities.
    b. Roundabout
        i. Signalized or unsignalized intersection where all entering vehicles yield to circulating traffic.
    c. Arterial
        i. Signalized street that primarily serves through traffic.
    d. Highway
        i. High speed road connecting major areas or arterials with limited intersections.
    e. Freeway

    i. Similar to highway, but without any traffic interruption.

f. HOV lane
    i. Exclusive lane for vehicles with defined number of occupants, including buses, carpools, which may be used by other traffic in certain circumstances.

g. HOV bypass lane
    i. Exclusive on-ramp lane for vehicles with a defined minimum number of occupants.

h. Ramp
    i. Short segment of roadway connecting two roadway facilities.

i. Auxiliary lane
    i. An acceleration or deceleration lane.

j. Reversible lane
    i. Roadway lane that changes direction during different hours of the day.

k. Truck lane
    i. Designated lane for commercial vehicles but not for public transit vehicles.

l. Bus lane
    i. Exclusive lane for buses, which may be used by other traffic during certain circumstances.

m. Toll plaza
    i. Facility where a payment transaction for the use of roadway.

n. Light-rail line

i. Railway system

3. Travel Mode
    a. SOV
        i. Single Occupancy Vehicle
    b. HOV
        i. High Occupancy Vehicle
    c. Bus
        i. Mass transit system using existing streets and highways
    d. Rail
        i. Transit system for both light and heavy rails
    e. Truck
        i. Heavy goods vehicles used for transporting goods versus public transportation
    f. Motorcycle
        i. Motor vehicle with maximum two occupancy.
    g. Bicycle
        i. Manual vehicle with maximum of single occupancy
    h. Pedestrian
        i. Individual travelling on foot
4. Management Strategy using Intelligent Transportation Systems (ITS)
    a. Freeway Management
        i. Freeway control, including ramp metering, dynamic message signs (DMS), highway advisory radio (HAR), etc.
    b. Arterial Intersection

   i. Signal timing, geometric improvement, LOS analysis, etc.

c. Arterial Management
   i. Dynamic signal algorithms, coordinated signalization, etc.

d. Incident Management
   i. Incident detection capabilities to minimize impact on traffic and traveller safety.

e. Emergency Management
   i. Ability to manage emergency vehicle response, including police, fire, medical, and hazardous materials response teams.

f. Work Zones
   i. Availability of traffic control during construction or maintenance while minimizing the impact on travellers and enhances safety of workers.

g. Special Events
   i. Ability to manage planned events that minimizes impact on traffic flow, such as during sports events, road parades, etc.

h. Advanced Public Transportation System (APTS)
   i. Using advanced technologies for operations, maintenance, traveller information, planning, and management functions for transit agencies. Usage of fleet management, traffic signal priority, etc.

i. Advanced Traveller Information System (ATIS)

   i. Using signage for real-time traffic conditions or fixed transit schedule information to multi-modal travellers to support mode and route selection to travellers.

j. Electronic Payment System
   i. Electronic payments for tolls, transit fares, and parking to enhance time for each transaction which favourably improves traffic flow or queuing at facilities.

k. Rail Grade Crossing / Bridge Opening Monitors
   i. Allows the diversion of traffic when bridges are open or crossing of railways through management of positive barrier systems and detection of approaching trains or ships.

l. Commercial Vehicle Operations (CVO)
   i. Fleet management that allows communications between drivers.

m. Advanced Vehicle Control and Safety System (AVCSS)
   i. Detection and warning of collisions to improve traveller safety.

n. Weather Management
   i. Automated collection of weather conditions to detect hazards, such as fog, wet or icy road conditions.

o. Travel Demand Management (TDM)
   i. Carpool programs, park-n-ride lots, etc.

5. Traveller Response
   a. Route Diversions

    i. Detects changes in travel routes, including pre-trip route diversion and en-route diversion

  b. Mode Shifts

    i. Detects changes in travel modes (such as monitoring the occupancy of park-n-ride lots or transit fares sold in any given day)

  c. Departure Time Choices

    i. Detection in changes in the time of travel

  d. Destination Changes

    i. Detection of change in travel destinations due to new traffic generators (i.e. opening a new hypermarket in a community taking away traffic for hypermarkets that are further away)

  e. Induced/Foregone Demand

    i. Estimates induced demands or foregone trips through implementation of traffic management strategies.

6. Performance Measures

  a. Level of Service (LOS)

    i. Measuring operational conditions within a traffic stream based on service measures, including speed, freedom to manoeuvre, traffic interruptions, etc.

  b. Speed

    i. Rate of distance per unit of time

  c. Volume

    i. Number of vehicles passing a road segment in a specific time interval

d. Travel Time

    i. Average time for vehicles traversing a facility, including control delay.

e. Travel Distance

    i. Space distance between origin and destination.

f. Ridership

    i. Occupancy of passengers on the transit system

g. Average Vehicle Occupancy (AVO)

    i. Average occupancy per vehicle including public transportation, such as buses

h. Volume to Capacity Ratio (v/c)

    i. Ratio of flow rate to capacity

i. Density

    i. Average number of vehicles within a space segment of road facility

j. Vehicle-Miles of Travel (VMT) / Person-Miles of Travel (PMT)

    i. Total distance travelled by all vehicles in a road segment during a specified time period

k. Vehicle-Hours of Travel (VHT) / Person-Hours of Travel (PMT)

    i. Total travel time spent by all vehicles in a road segment during a specified time period

l. Delay

    i. Additional travel time spent by travellers during lower than free flow speeds, signal operations, and turn penalties

m. Queue Length
    i. Length of queue waiting to be served due to reaching travel demand over capacity of road (or during incidents).

n. Stop Penalties
    i. Number of stops experienced by a road segment, including signal phasing.

o. Crashes
    i. Average number of crashes expected in a segment of road

p. Incident Duration
    i. Average duration of incidents, including crashes, vehicle failure due to mechanical or tire problems, etc.

q. Travel Time Reliability
    i. Expected probability of reaching higher travel demand due to incidents, weather conditions, special events, etc.

r. Emissions Fuel Consumption
    i. Predicted emissions for each pollutant type in a network depending on average emissions of vehicles using roads (broken down to percentage of types of vehicles)

s. Noise

i. Sound levels produced by traffic

t. Mode Split

i. Percentage of travellers using each travel mode.

u. Benefit / Cost Ratio

i. Quantifying the ratio of monetary benefits to total costs of traffic improvements and maintenance.

There are different types of simulations that consider different data inputs. It is assumed the maximum number of data necessary for any type of simulations to be applied in the GIS data model.

3.5 Environmental Data Considerations

The environment is one of the most important aspects that need to be considered when evaluating different road design alternatives. The regret based on the effects of the environment in the long-term may also play a significant role in decision-making. However this research gives the freedom to the user to specify a weight for such consideration. The environment and the planning model move hand in hand in the decision process. When working with roads construction alternatives, it is important to consider how the project would affect the environment. Within a GIS model, it is important to consider certain data that would usually make up an environmental impact assessment. The scope of this research is not to provide the actual process for an environmental impact assessment, but presumes that such a study is done, and the data that are necessary to make the assessment would become part of the GIS data model.

Required GIS environmental data as inputs to the GIS model:

1. Geomorphology
   a. Sloping
      i. Landscape inclination
      ii. Relief
2. Soil
   a. Weight-bearing capacity
   b. Shrink / Swell
   c. Permeability
   d. Erodibility
   e. Flora
   f. Soil type
   g. Slope
   h. Rainfall
   i. Water table (seasonal range)
   j. Fertility
3. Hydrology
   a. Water supply
   b. Sediment trapping
   c. Nutrient trapping
   d. Aesthetics and scenery
   e. Shoreline erosion
   f. Groundwater quality
   g. Water quality
4. Hazards / Climate
   a. Air Quality (emissions)

b. Floods
c. Hurricanes
d. Tornadoes
e. Landslides
f. Earthquakes

5. Fauna
    a. Wildlife habitats
6. Flora
    a. Vegetation
7. Noise Pollution

The environmental data is considered to include as inputs of the analysis required to understand what mitigation costs are necessary due to the roads project. The purpose of such an assessment is to help decision-makers understand the requirements of sustaining the ecology, which is partially part of the planning model. Although in this model it helps in understanding the cost of mitigating impacts on the environment, it also helps in understanding what kind of mitigations are necessary to keep a sustainable area. Therefore, similar to a planning model, this model also includes the governmental regulations that necessarily encompass the types of mitigations necessary for each type of impact that are related to the data mentioned above.

3.6 Roads Construction Data Considerations

From a construction perspective, it is important to consider the different data that are necessary, which include the same data used in models discussed earlier. For example, when looking at earthwork requirements,

it is important to have geotechnical information available about the types of soil. However, what is important to include in this section is data that pertains directly to the method of construction.

The construction method is important to understand. However, usually, when looking at different alternatives of roads construction, it is not as easily identifiable the best alternative. Therefore, the construction method is usually not scrutinized in the decision process for choosing the best alternative, although it is debatably as important.

The challenge when looking at this factor is the base fact that there are different construction method alternative for each road alternative. Therefore, the question is whether or not it is important to consider the alternatives of roads construction in the GIS model.

For roads construction, the main costs are based on i) earthwork, ii) substructures, and iii) superstructures. For each of those, the cost of i) equipment, ii) materials, and iii) labour are considered. For each of those, they are divided into two main categories i) cost of mobilization, and ii) cost of construction.

Perceiving costs of construction, it is necessary to understand that the cost of material would usually not be changing, except of course to the marketplace value of the materials. In other words, the cost of materials is independent of the construction method used. Whereas the cost of equipment and labour is very much dependent on the construction method employed for the job.

For purposes of development of performance indicators, the method of construction would not be much scrutinized, but a general idea of the cost of construction is considered. However, the data required to estimate the cost on construction is the following:

1. Geomorphology
2. Geotechnical
    i. Soils
    ii. Water table
3. Infrastructure
    i. Existing utilities
    ii. Existing roads
4. Topography
    i. Buildings
    ii. Plants
5. Materials
    i. Re-usability
    ii. Recyclable
    iii. Waste Management
6. Equipment
7. Labour

Furthermore, this study would consider the general cost of construction assuming that the actual value of construction would be an input to the model.

3.7 GIS Data Accuracy

Since GIS analysis is only as good as the data itself, it is important to understand what considerations of accuracy need to be allowed in the model and the topology rules between such data. For example, in the macro-level, it may be understood that precision is not critical. Arguably, the accuracy of the data in the macro-level may not be fatally significant to the model as well. However, when looking from decision theory perspective, one needs to analyze the risk and regret from outcomes caused by inaccurate data. Hence, it is not only imperative to evaluate the risk from having a comprehensive model that might be inaccurate in its structure and model, but also that of the data itself. Next chapter evaluates, from a decision theory perspective, the assessment of risk and regret functions that need to be considered in the analysis process.

4. To Regret or Not to Regret

4.1 Introduction

Boscoe Pertwee, an 18th century author, once said, “I used to be indecisive, but now I am not so sure.”

Decision theory is a realm of mathematics that deals with decision processes. Decision theory and regret theory have always been intertwined with each other. People always make decisions every moment of their lives. Not one second passes by without a decision being made. If you are reading this, then you have already decided that you would do so.

Everyone decides, even the indecisive ones during their indecision. Decisions are fundamentally made of three parts, i) yes, ii) no, and iii) abstain. Most people believe that abstaining from an opinion is indecisiveness. As a matter of fact, they already made a decision. Their decision is to refrain from making any. All decisions can someday be regretted. Deciding to abstain could be regretted as well.

For example, five people could be voting between A and B. Two vote for A, one votes for B, and two abstain. If, in the future, it were found that A is working well, then the two, who have abstained, will not regret their decision to abstain. If, in the future, it were found that B would have been better, then the two, who have abstained, would regret their decision to abstain, since they could have voted for B, such that it would be chosen.

If, in the future, it were found that neither A nor B are good, then the two, who have abstained, would not have regretted their decision. If the probability of those three outcomes is equal, then, probabilistically, you have a better chance not to regret if you decide to abstain. However, this statement is not completely true as you will see later.

Different decisions carry various rewards and risks associated with it. Within regret theory, reward and risk are factors of the regret function. Every day we make different decisions, some may not be too significant, such that we would not significantly regret it if we were wrong, like not putting enough flour while baking a cake. Other decisions may be too significant, and therefore can be significantly regretted, like deciding to purchase a home. At the end, decisions need to be made. That is the role of any decision-maker.

Fundamentally, decisions need to be made, even if they were wrong. Why? If we make a decision and later find that it was a good choice, we would be happy. If we decide on something and later find out it was the wrong decision, we would regret it, but at least we will learn from our mistake. However, if we decide not to make a decision, then we will neither learn nor be satisfied, and for that, we will regret it twice; once for not making the right decision and another for not learning what the best decision would have been. So now, even if probabilistically you have a better chance not to regret what you abstain if the probabilities between the outcomes are equal, your regret would be higher, if you did, than if you made the wrong decision. However, philosophically, regret is further more complex than this. Thus, this statement is not completely true also,

since your regret depends on the situation, the initial conditions, and the risks involved.

Geographic Information Systems (GIS) is a Decision Support System (DSS). Therefore, it is only inherent to utilize GIS to spatially analyze existing transportation and traffic models, while including regret theory into the existing models.

Decision theory is normative or perspective. In other words, it identifies the best decision to take, assuming informed ideal conditions are available. However, still taking into account uncertainties of the risks associated. Within the process of decision theory, to formulate a better understanding for a decision, a full consideration of all factors need to be made. Therefore at first, the risks and rewards for each road design alternative are determined, before the regret factor that is associated to such a decision is evaluated.

Different alternatives might have different rewards, since transportation models utilize multi-criteria evaluations, which include traffic flow and safety, planning and environmental impact, and financial costs. This, in decision-theory, determines the dominance of the action taken. Somehow, decisions are objective-driven with different weights given to each. By such, balancing between risks and rewards, regret is born.

Brim (1962) divides the decision process into the following five steps:

i. Identification of the problem.
ii. Obtaining necessary information.

iii. Production of possible solutions.
iv. Evaluation of such solutions.
v. Selection of a strategy for performance.

4.2 Understanding Decision Theory

Imagine you arrive into a town in the middle of the night and you are trying to find a motel to stay. As you enter the town, it is apparent that everyone in town is asleep, so there is no one for you to ask directions to the nearest motel, if in fact a motel exists. The road you are travelling on divides into a fork that shall be called Road A and Road B. Once you drive through one of them, you cannot take a U-Turn. Hence, your decision cannot be changed once the action has been taken. For the lack of any map, you have absolutely no idea which road you should take. Through intuition, you expect a 50% chance of making the right decision due to strict uncertainty. This is also known as Laplace's principle of insufficient reason. Laplace (1825) argues that knowing nothing about the true state of nature (θ) is equivalent to all states having equal probability. At that moment, you understand that there are four possibilities, and that you have to decide between two actions, or decide to be indecisive.

The four different possibilities include:

p_1: There is at least a motel along Road A.

p_2: There is at least a motel along Road B.

p_3: There is at least a motel along both Roads A and B.

p_4: There are no motels on either road.

The actions you can choose from are either:

a_1: Drive along Road A.

a_2: Drive along Road B.

a_3: Indecisive.

Table 4.1 summarizes the events of your chances of finding a motel with strict uncertainty. It is found that your intuition is correct, there is a 50% chance that your decision is correct of finding a motel, if you drive along either road, and of course 100% chance of not finding a motel if you stay where you are, since this is the initial state of nature.

Table 4.1 Probability of finding a motel in strict uncertainty

	a_1	a_2	a_3
p_1	Find	Does Not Find	Does Not Find
p_2	Does Not Find	Find	Does Not Find
p_3	Find	Find	Does Not Find
p_4	Does Not Find	Does Not Find	Does Not Find

Table 4.2 summarizes the events of regretting your decision compared to the reality of things. For example, if there were no motels on either road, and you choose one of them, the decision may not be regretful, since in reality there is no motel on the other road either. Therefore, the probability of regret is 25% if you drive along either road, and 75% chance of regret if you stay where you are.

Table 4.2 Probability of regret

	a_1	a_2	a_3
p_1	Does Not Regret	Regret	Regret
p_2	Regret	Does Not Regret	Regret
p_3	Does Not Regret	Does Not Regret	Regret
p_4	Does Not Regret	Does Not Regret	Does Not Regret

From a probabilistic point of view, regret (R) is a subset of a negative outcome (O^-), and therefore, positive outcome (O^+) and regret (R) are mutually exclusive, since axiomatically, you can never regret a decision with the right outcome. A positive outcome is defined as the outcome being as expected from a model or better. For example, if an intersection is designed for a Level of Service (LOS) C and the actual state of nature, after the intersection was constructed, is found that it really is LOS B, then that is considered a positive outcome as it is higher than the expected. Principally, getting a negative outcome is a risk. However, just as in the example above, it is also possible not to regret a negative outcome, whereas the decision is still correct. Fundamentally, not taking a decision is still considered an outcome, and can either be right or wrong, since it means that the decision is to keep the current situation as it is. Thence, abstaining from taking a decision, paradoxically, is essentially considered a decision, which does affect the evaluation of regret.

Mathematically, this can be expressed as follows:

$$P(O^+) + P(O^-) = 1 \qquad (Eq.\ 4.1)$$

$$P(R) \leq P(O^-)$$

Within decision-theory, there are different models to evaluate the best action to take. These models are known as decision criteria. When evaluating between the two actions of whether or not to take Road A or Road B, each action has the same ranking, as shown in Table 4.3.

Table 4.3 Probabilities of outcome and regret

	$P(O^+)$	$P(O^-)$	$P(R)$
a_1	0.5	0.5	0.25
a_2	0.5	0.5	0.25
a_2	0	1	0.75

Thence, whichever road you drive along, there is an equal probability of arriving to a positive outcome and an equal probability of regret. Whereas, if you remain indecisive, then the probability of a negative outcome is 100% and the probability of regret is 75%. If all values of reward and risk are equal, then taking a decision driving along either road is always better than to stay where you are.

An interesting conclusion is arrived at regarding strict uncertainty if the current state of nature is unsatisfactory. When encountering strict uncertainty of the consequences, many people tend to be hesitant to take decisions. If no more data can be collected to reduce the value of uncertainty, then philosophically, a decision is always better made, because your regret will be higher if you do not.

Similarly, when there exists a strict uncertainty of the consequences, but the risks and rewards are of different values, then taking a decision is easy. If a passenger on a plane is suffering from heart attack symptoms, a physician without the necessary tools may not immediately able to identify whether or not the situation is that of a heart attack or a panic attack, which would not necessarily require immediate emergency. If the pilot asks the physician whether or not to make an emergency landing, a good physician will always choose making an emergency landing,

because although you are under strict uncertain consequences, which means that the probability of either are equal, the values of your risk are different. If the situation was truly of a heart attack and you do not decide to make an emergency landing and the person dies, your risk value is greater and therefore, your regret value is greater as well, even though the probabilities are the same.

4.3 Decision Criteria

There are different criteria for decisions. One of which is known as the MAXIMAX decision rule. The maximax decision rule relates to an optimistic decision-maker. The rule means that a maximum reward is sought no matter how high the risks are. When evaluating alternative road designs, and especially road safety, this criterion would not be ideal. This criterion is actually contradictory of cost/benefit analysis, which is usually used for roads construction. It means, if you pay $1,000,000 to build a road with LOS C or pay $1,000,000,000 to build a road with LOS B, you will always choose the latter simply because it is more rewarding. In public decision-making, some may find this to be an irrational methodology. Thus, this criterion is not considered in this study to its fullest extent.

Another criterion is that which relates to a pessimistic decision-maker. This criterion is known as the MINIMAX decision rule. This rule attempts to minimize the maximum loss. The connotation of this rule is to have the lowest risk no matter how attractive are the rewards of other alternatives. Using this rule implies a conservative approach. When dealing with roads alternatives and road safety issues, taking a conservative

approach might be crucial, but not perfect, as it ignores many of the rewards data. It means that if you pay $1,000,000 to build a road with LOS C or pay $1,010,000 to build a road with LOS B, you will always choose the former, even if it meant the second alternative costs $10,000 more, but is still more rewarding. Thus, this criterion is not considered in this study to its fullest extent.

Hurwicz (1951) criterion attempts to compromise between the maximax and minimax rules, by giving each a percentage weight. However, neither the maximax nor the minimax rules apply the regret function developed in the same year by Savage (1951). Hence, this criterion as its predecessors would still fall short, as they would continue to ignore essential data due to uncertain consequences.

To make sure that the regret function is included in decision-making, a criterion known as Savage Minimax Regret criterion has been developed. This criterion focuses on avoiding regrets that may result in composing a non-optimal decision. Although regret is a subjective emotional state, the assumption is made that it is quantifiable in linear relation to the rewards.

Maximum Likelihood (Modal) criterion considers only the state of nature most likely to occur as the basis for the decision, excluding all other outcomes. This criterion is the most widely used decision rule employed by statisticians and decision makers. However, since this criterion almost ignores most of the data, the decisions are being made from a position

of ignorance. Thus, this criterion is not considered in this study to its fullest extent.

Laplace Insufficient Reason criterion is an alternative approach in decision theory. This criterion makes use of explicit probability assessments regarding the likelihood of the sates of nature (Hartigan 1983). Therefore, it makes use of almost all available data. The Laplace argument makes use of Bernoulli's Principle of Insufficient Reason. To address uncertainty, probability theory is used for each state of nature. This study considers this criterion to identify the decision process of different roads alternatives.

4.4 Comparison of Road Design Alternatives

Deciding between different road designs is not simple. Geometric alternatives may be simple, such as widening a lane, or drastic, such as building underpasses and flyovers to reduce conflict points. For example, such alternatives could be to determine whether or not a left turning lane needs to be introduced in the N-S direction, allowing a bicycle lane on only one side, and changing the layout of the parking towards the East, as compared between Figures 4.1 and 4.2.

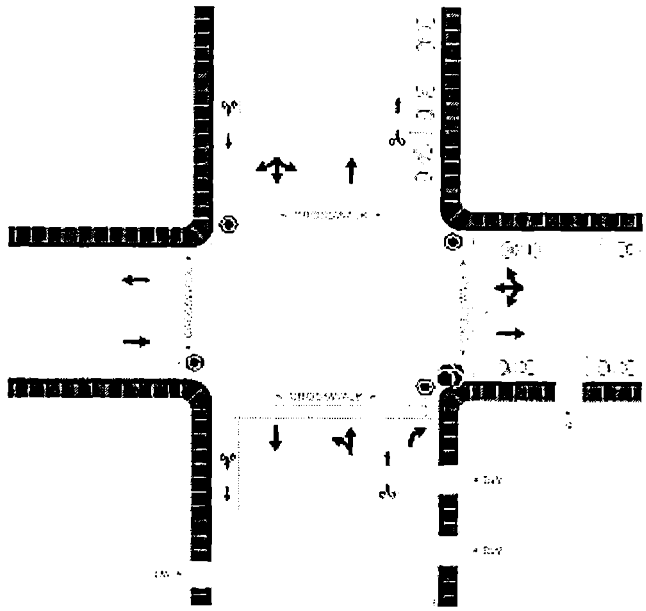

Figure 4.1 FIRST ALTERNATIVE

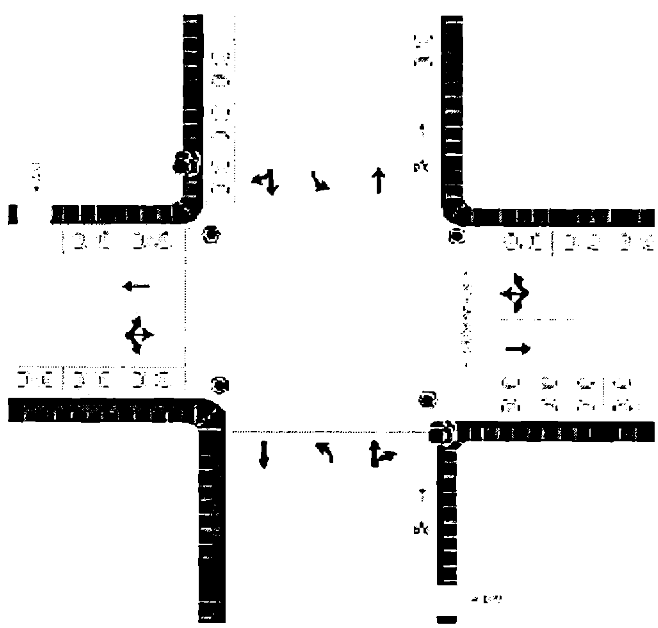

Figure 4.2 SECOND ALTERNATIVE

As discussed in this study, many models exist that can evaluate performance indicators for planning, traffic flow and safety, construction economics, and time. Each of the performance indices of different models would require diverse types of data, as discussed earlier. Those performance indicators can be, but are not necessarily objective driven. However, to reach an optimal decision, regret theory needs to be considered for each of the performance indicators.

Consider PI_{ij} is a performance indicator, such that the following may apply:

PI_{1j}: Performance Indicator for planning

PI_{2j}: Performance Indicator for traffic flow

PI_{3j}: Performance Indicator for traffic safety

PI_{4j}: Performance Indicator for construction economics

PI_{5j}: Performance Indicator for time of completion

Conceptually, this methodology can be applied to as many *m* performance indices as required. Since these performance indicators may be evaluated using different model techniques, they would need to be normalized, such that it would be comparable with one another. Nevertheless, each individual performance indicator must be applied to all the alternatives. For example, if Synchro® was used to evaluate for the traffic flow performance indicator, then it must be used to evaluate all the alternatives. This is essential to remove any bias in the evaluation of a performance indicator that may arise to the usage of different quantification methods between different models.

In this study, it is assumed that the larger the performance indicator, the better, and also assumes that performance indicators are positive values. However, since this may not be true to some existing models, which reverses the method. Then, for performance indicators where the smaller value is better shall be inversed, prior to normalizing each performance indicator for consistency purposes. The worst performance indicator is presumed to be zero.

Assuming there are *n*-number of alternatives to evaluate, normalizing between them would require the following step for each performance indicator converting it to a normalized performance indicator, NI_{ij}:

$$NI_{1j} = \frac{PI_{1j}}{MAX\,(PI_{1j})} \qquad \textit{(Eq. 4.2)}$$

This would mean that each normalized performance indicator is bound by the following:

$0 \leq NI_{ij} \leq 1.$

Essentially, normalized performance indicators are only evaluated to express the relationship between different alternatives in the same study. Important to note, it cannot be used to compare between one alternative in one study group and another alternative from a different study group. Normalized performance indicators can be expressed in a matrix, where each column is an alternative showing the result of evaluating all performance indicators to it.

$$\begin{bmatrix} N_{11} & \cdots & N_{1n} \\ \vdots & \ddots & \vdots \\ N_{m1} & \cdots & N_{mn} \end{bmatrix}. \qquad \textit{(Eq. 4.3)}$$

Models, whether planning, traffic, or others, are not perfect. They may simulate what the outcome may be but there is always an amount of uncertainty. Different models have different levels of uncertainty. The likelihood the model is correct may be determined through different criteria determined by the levels of uncertainty or statistics. This means there exists a probability, P_{ij}, that a positive outcome is reached for each of the performance indicators of every alternative. However, those probabilities would not necessarily be the same even if the same model is used to evaluate each alternative.

This is further expounded by the following example. If the parameters using a specific model give a high predictability for a four-legged intersection, its predictability of a roundabout may not be as accurate. Therefore, the probability that a positive outcome is reached, if the design for a four-legged intersection, is higher than when evaluating for a roundabout, using this specific model. Therefore, it can be identified that different models may be biased. For example, a model can be liberal when analyzing a four-legged intersection and more conservative when analyzing a roundabout. A probability matrix for a positive outcome for each performance indicator can be expressed as follows:

$$\begin{bmatrix} P_{11} & \cdots & P_{1n} \\ \vdots & \ddots & \vdots \\ P_{m1} & \cdots & P_{mn} \end{bmatrix}. \qquad \text{(Eq. 4.4)}$$

Due to uncertainty, as there is a probability for a negative outcome, there is, therefore, a probability to regret the decision made, which is defined as $(1 - P_{ij})$. In some models, the probability of not having a positive outcome may be known. Therefore, in such cases, decisions are under risk. However, most decisions are made under uncertainty. For example, the Big Dig project in Boston was later influenced by unexpected discoveries of old debris underground and running over the budget. Reconstruction of interchanges in Dubai was due to unexpected population and development growth. In the case study of building a highway in the city of Plzeň in the Czech Republic, some data was unknown, such as the geology of the area, which if were known, the decision might have been different.

Since different models have been tested and possibly calibrated, it is not fair to say that evaluation of different road design alternatives are under strict uncertainty. Sometimes errors may be known and the likelihood identified. Thence, this study will mainly consider decisions under uncertainty, but not to the extent of ignoring known risks, if available. Therefore, partial probabilistic knowledge of the outcomes is recognized in this study. Within decision theory, a utility function is generated. This study focuses on such utility function, and more accurately on the expected utility function, which is based on a probability-weighted utility

theory that is further discussed in details later in this study. The weight matrix for each performance indicator is expressed as follows:

$$w \in \left[w_i \quad \cdots \quad w_n \right]. \qquad \textit{(Eq. 4.5)}$$

Bell (1983) explains that regret is measured as the value difference between the assets actually received and the highest level of assets produced by other alternatives. However, regret can also be understood as the desire to avoid uncertainty.

This study approaches regret from a multivariate process, since there are different objectives, which may or may not conflict with each other. Although this study does not dwell into optimization, it is appropriate to identify that optimizing the performance indicators might be useful. Regret, however, is identified as the amount of gain that might have been expected for each performance indicator, if a different alternative was used.

The quality of a decision depends on the quality of alternatives and the ability to develop a detailed analysis for selection. However, as in any analysis, an analysis is only as good as the data inputs. If the data is not accurate or insufficient, the analysis will therefore be similarly inaccurate. When working with data, it is important to consider the macro-level and micro-level data for the selection analysis. In Chapter 3, the GIS data that is necessary to make a decision model that is able to select between alternatives are introduced. Not only is it important to look at the accuracy of the data, but also its completion. Sometimes, when

looking at different alternatives, some details that might change the outcome of the whole construction process are ignored. For example, when neglecting the fact that Boston is on a landfill, unexpected shipwrecks were discovered buried under the city during excavation of the Big Dig project tunnels. Hence, sometimes it is not only the quality of the data that is only important, but also considering the completion of this data.

The process for evaluating alternatives starts by proposing an action. Then, it is necessary to define the objective of such an action, as in what is the purpose. Then to develop different alternatives, which are considered reasonable and meet the objective. The alternatives are then evaluated from a macro-level point of view, which include the planning and environmental models. This analysis will eliminate some of the alternatives. The remaining possible candidates are then analyzed in the micro-level, which include a full traffic study. Finally, the alternatives are given a score each according to the criteria and the weight given for each of the major factors.

If the expected utility function within the context of decision theory does not agree with the actual state of nature, θ, then regret is defined. Though models can be used to give an expectation of the future state of nature, accuracy is always a concern.

A classical school of thought of urban planning states that planners can define how a city is planned. However, a more modern school of thought states that a city is planned ad-hoc, depending on the ever-changing

economy of a global market. Many cities in the world have become a hub for international technology companies. This has allowed their economies to move and therefore, spur development. Most of this development has not been planned from within a master plan. Developing cities in this age occur not only due to a 20-year strategic master planning, but mainly due to other factors that are usually beyond the control of planners.

There is a probability that the future state of nature (θ) would be worse than expected. This is not only due to unexpected planning and traffic flow, such as the cases in the reconstruction of interchanges in Dubai, but also due to unexpected overrunning the budget of the cost of construction, as in Boston's Big Dig, and other factors.

Classically, regret is defined as the value lost, if another alternative has a higher yield for a specific performance indicator. Therefore, loss is evaluated as follows:

$$L_{ij} = N_{ij} - MAX\lfloor N_{ij} \rfloor. \qquad \textit{(Eq. 4.6)}$$

This evaluation of loss assumes that the relationship between reward and risk are compared in linear form. Hence, the loss matrix is expressed as follows:

$$\begin{bmatrix} L_{11} & \cdots & L_{1n} \\ \vdots & \ddots & \vdots \\ L_{m1} & \cdots & L_{mn} \end{bmatrix}. \qquad \textit{(Eq. 4.7)}$$

If the action of a specific performance indicator in an alternative is already the highest among other alternatives, then according to the equation above, it receives a value of *zero*, since no known opportunity in terms of regret is expected. However, this definition of regret is used loosely. In reality, this definition is restricted to the value that would have been gained for a specific performance indicator, if another alternative yielded a better result. However, when looking at regret, though this valuation is partially correct, it does not factor the probability that the model used to get the performance indicator will actually yield the expected values.

As discussed earlier, there is a probability that the results of road design may not yield the expected utility. For example, if an alternative is the best in each performance indicator, then according to the equation of regret above, it will have a value of *zero* regret. However, after completion of the construction, if the performance was lower than expected, then it would still be regretted. Also, the worse the actual state of nature (θ) is, the higher the regret. This means that regret in itself is a function in which the value would normally increase the lower the expected utility is.

For example, the performance indicator of cost is evaluated between two alternatives, A and B, with all other performance indicators equal. Alternative A costs \$10,000,000 and alternative B costs \$15,000,000. If alternative A was chosen, then according to the definition of regret above, the regret value for the cost performance indicator is *zero*.

However, if during construction it is found that due to unexpected projections, the cost would overrun its budget by another $10,000,000, then the cost of alternative A is actually $20,000,000, which is $5,000,000 above the cost projected for alternative B. Assuming the cost of alternative B is not affected by the unexpected projections, then the choice of alternative A is regretted. Therefore, the definition of regret, as defined earlier, falls short from being accurate.

On another note, the higher the cost is overrun, the higher the value of regret. Thence, a probability function of expected values needs to be used to evaluate the value of the regret function. It is apparent that for all the parameters discussed in this research the worse an unexpected event occurs, the higher the value the regret. Therefore, regret is assumed as a continuous function and not necessarily discrete, although in most literature, regret function is a discrete event.

Essential to note that regret is not necessarily quantified as a continuous function, as stated earlier. The definition of regret as stated earlier can be loosely expressed as the maximum amount of opportunity lost due to the existence of an alternative that might have been chosen. However, this denotes as comparing between different alternatives and no other. For this decision flow to make sense, it is strictly used as a comparison tool between different alternatives, and it assumes that if there is an unexpected event that might occur in the future, then it is as likely to occur in any of the alternatives equally. For example, if the traffic volume increases to unexpected values in the future, then it is assumed the same number would increase for any alternative.

Nevertheless, this assumption is flawed. If the road capacity is restricted and there are other road alternatives, then the volume of traffic may increase less compared to what would happen if the road has a higher capacity. The reality of this event depends on the driver's behaviour. If an alternative exists and can accommodate a higher capacity, more drivers would like to travel through it than on an alternative route; whereas, if the capacity of the road is restricted, more drivers would opt to choose an alternative route with a higher capacity. On another note, if the capacity of a road is restrictive, then development along the road will be restricted as well, and therefore, even if an increase of traffic volume occurs to unexpected values, it may not be as high as it would if the road design would have allowed more development.

Furthermore to this analysis, there could be an error in the computation of the expected performance indicators for each alternative. There is a possibility that none of the alternatives compared would have had a scenario for an unexpected event. Otherwise, it would not have been unexpected. Thence, there is room for regret due to this uncertainty.

As a solid definition of regret, it is the loss of the maximum opportunity. From a deterministic point of view, the actual future state of nature (θ) is compared with the assumed values that may still be objective-driven for each performance indicator. The value of each performance indicator can be re-evaluated at any future time and compared with the original assumed values. Once the values become known, regret is easily identified, given the initial priori conditional objectives.

The weighted value of the opportunity lost can be evaluated as regret and expressed as follows:

$$R_{ij} = w_{ij} \cdot (1 - P_{ij}) \cdot (L_{ij}) \qquad \textit{(Eq. 4.8)}$$

This expression includes the value of regret due to an expected opportunity lost, when comparing different road design alternatives. It does not include the opportunity lost compared to the future state of nature (θ).

The true state of nature (θ) will only affect the regret function if the true state of nature (θ) exceeds the maximum expected value of the performance indicator in any of the alternatives, which would mean there is a higher value in the opportunity lost. Also, the true state of nature (θ) will also affect the regret function if the models used to evaluate the performance indicators are not accurate and therefore the values are skewed or were in error (ξ).

4.5 Error Considerations for the Comparison of Road Design Alternatives

In many cases, if the models were not accurate, then this inaccuracy will be similar in the evaluation of all alternatives. Therefore, since the same error (ξ) is instituted in the evaluation of the performance indicator in all the alternatives, this error affects the performance indicator in the same

way for all the alternatives compared. Thence, it would not change the ranking values between the compared alternatives.

There are some cases, however, that the model used to evaluate a performance indicator may give different inaccurate measures for each alternative. For example, some traffic flow models may be more accurate for signalized intersections than roundabouts. Therefore, if the values were compared, the inherent error (ξ) in the roundabout analysis may be higher than that of the signalized intersection when both designs are compared, and therefore this error needs to be considered.

The evaluation of each performance indicator may have a different error, which would give it a range, such that the error for each performance indicator can be expressed as follows:

$$\xi = \pm e \%. \qquad \textit{(Eq. 4.9)}$$

This error is propagated from those inherent within the evaluation of each performance indicator, due to the lack of data, or otherwise due to the model itself. The confidence level needs to be consistent in the evaluation of all the alternatives to avoid any bias in the performance indicators. The error can be statistically driven for each model used comparing the results given by the model and the actual results later evaluated as the true state of nature. This provides a comparative result with a confidence level allowing the evaluation of the range of values for each performance indicator.

To accommodate the error (ξ), a range for the performance indicators would be evaluated and normalized. As a conservative approach, it is recommended to evaluate the normalized values based on the lowest value in the range over the maximum value of all the alternatives for each performance indicator. This methodology attempts to reach a compromise with the MINIMAX rule by evaluating the maximum loss expected. By definition, this also means that the alternative with the highest performance indicator would still have a possibility of an opportunity lost as its lowest range is being compared with the highest. This is due that to the expectation that the true state of nature (θ) might reach the highest range value if more precision was established or that the highest range from an alternative is different than the alternative with the highest midpoint. The methodology proposed identifies that maximum expected error (ξ) in the evaluation of performance indicators.

Error continues to be assumed with linear relationship and as a continuous function for regret. Therefore, when considering error in the evaluation, the following normalized indicator is used from Eq. 4.2:

$$NI_{1j} = \frac{PI_{1j}}{MAX(PI_{1j})}$$

Therefore, if an error exists, then each normalized performance indicator is bound by the following, in which it would be strictly less than 1:

$0 \leq NI_{ij} < 1.$

The final regret matrix, based on a weighted probability of the opportunity lost based on *Eq. 4.8* is represented as follows:

$$R_{ij} = w_{ij} \cdot (1 - P_{ij}) \cdot (L_{ij})$$

$$\begin{bmatrix} R_{11} & \cdots & R_{1n} \\ \vdots & \ddots & \vdots \\ R_{m1} & \cdots & R_{mn} \end{bmatrix} \qquad \textit{(Eq. 4.10)}$$

Imperative to note, if the performance indicator between two alternatives are too close to be called equal, how would regret be evaluated? For example, if all performance indicators are equal, except for the cost, where alternative A costs $10,000,000, while alternative B costs $10,001,000, would it be practical to conclude that alternative A is better because it is 0.01% cheaper? This logic does not only apply to cost, but to all other performance indicators as well. This opens the door to fuzzy logic. More investigation and research need to be done in the future to factor fuzzy logic within the regret matrix. Section 4.8 discusses how further research in fuzzy logic may allow for more incite in taking decisions with values that are not significantly different from each other.

4.6 Model Sensitivity

When dealing with numbers within a matrix, it is always interesting to see how sensitive the outcome is, if a variation in the numbers occurs. The regret model proposed is an aggregation of different expert models that exist in their current fields, such as planning or traffic, and each individual model has an expected probability of a positive outcome, and

a range of expected error, as described earlier, which can be concluded through statistical computations comparing the results of those models with actual values obtained from reality. Therefore, most values in the regret model are solid.

The regret model proposed is a probability-weighted model. Drazen (1998) discussed the importance of a probability weighting function in decision theory. A theoretical discussion of the properties of a weighting function is also found in Tversky and Wakker (1995). If it is safe to say that the probability matrix can be safely derived from actual statistical data, and therefore introduce the expected amount of error in the range of values in the regret matrix, the question holds is how will the weights affect the results of the model. It has already been stated previously that the regret model gives the decision-makers the freedom to choose their own strategy, in which the weights are based on. Nevertheless, although weighting is subjective, there are methods that can determine accurate attribute weights based on the strategy provided by the decision-makers.

A technique known as the hypothetical equivalents and inequivalents method (HEIM) has been developed specifically to deal with weighting strategies (Gurnani et al. 2003). The HEIM technique allows the decision-maker to invent hypothetical alternatives that are first compared. The use of hypothetical alternatives ensures that the decision-maker is not bias towards any one of the actual alternatives and state their preferences over the weighting results. Once the preferences over hypothetical alternatives have been stated, an optimization problem is formulated, where the attribute weights are set as design variables,

preference statements are set as constraints, and a pseudo-objective function that brings the sum of the weights to one is used. The standard optimization model is signified as follows:

$$\text{Minimize} \quad F(\mathrm{x}) = \left(1 - \sum_{i=1}^{m} w_{ij}\right)^2 \qquad \textit{(Eq. 4.11)}$$

$$\text{Subject to} \quad h(x) = 0$$

$$g(x) \leq 0$$

Where, *h(x)* and *g(x)* are constraints based on the decision-maker's preferences towards the hypothetical alternatives and '*x*' is the vector of attribute weights. To further understand how the constraints are constructed, consider the hypothetical alternatives H_1 and H_2 are the summation of the attribute weights multiplied by the normalized performance indicator for each hypothetical alternative as shown:

$$H_1 = \sum_{i=1}^{m} (w_{i1} \cdot NI_{i1}) \qquad \textit{(Eq. 4.12)}$$

$$H_2 = \sum_{i=1}^{m} (w_{i2} \cdot NI_{i2}) \qquad \textit{(Eq. 4.13)}$$

On the basis of the stated preference over the hypothetical alternatives, H_1 and H_2, an equality or inequality equation is determined to form the constraint *h(x)* for equality preferences and *g(x)* for inequality preferences. This method is used to determine the actual weights which are preferred by the decision-maker, and once those weights have been established, they are to be used to compare the actual alternatives in question. Using HEIM's method requires a number of hypothetical

alternatives that are equal to the number of performance indicators, such that the weights can be calculated as a system of linear equations.

Yet, there is one pitfall in using the HEIM technique in the regret model proposed. The HEIM's disadvantage is that it would work best when the multiple attributes are under certainty. Though the regret model also uses performance indicators that are under certainty due to the understanding of the actual models it is built on, it does not assume that certainty always exists. On the contrary, the regret model introduced in this research is mainly built under uncertainty, and thence the HEIM technique falls short in allowing reliable applicability in optimizing weights.

Multiattribute utility theory as introduced by Keeney and Raiffa (1993) and used in engineering design by Thurston (1991) and Li and Azarm (2000) has always used attribute weights, but the assignment of such weights have always been arbitrary. To overcome this problem, Gurnani and Lewis (2005) have developed a technique known as the robust alternative selection method (RASM). This technique ensures that the winning alternative is insensitive to changes in the values of the attribute weights.

To further understand the calculation of the robustness of the model, an overlap measure metric is evaluated. The overlap measure is a metric that combines the uncertain range of the performance indicator attributes for a given alternative and decision-maker's preference function for that performance indicator.

Consider $f_{ij}(x)$ to represent the probability density function (pdf) of the i^{th} performance indicator for alternative j. The decision-maker's utility function for the i^{th} performance indicator is denoted as $U_i(x)$. For each alternative j, the i^{th} performance indicator, defined as the overlap measure, is evaluated by

$$O_{ij} = \int_{-\infty}^{+\infty} f_{ij}(x) \cdot U_i(x) dx \qquad \text{(Eq. 4.14)}$$

where O_{ij} is the overlap measure score of the i^{th} performance indicator for the j^{th} alternative.

The integration limits are open-ended to infinity denoting that it is evaluated over the entire set of feasible values for that performance indicator, assuming it is a continuous variable. Nevertheless, if the performance indicator is discrete, the pdf becomes a probably mass function (pmf) and the integral is replaced with a summation.

Once the overlap measure is determined for all attributes for each alternative, a matrix is formed, in which the total score function is determined by multiplying the overlap measure with the performance indicator weight and summed over all performance indicators. The overlap measure index, therefore, incorporates the decision-maker's structure into the matrix, which now becomes a standard multiattribute problem under certainty, and thus, the HEIM method can then be used to solve for the weights. As the weights are found by using their sum as the objective function, theoretically, it is possible that different sets of

weights that satisfy all constraints and result in a different winning alternative. Consequently, it is important to have enough constraints initially that would restrict the feasible space. Unfortunately, it is not possible to determine a priori how many constraints would be required to sufficiently constrain the feasible space in order to obtain only one winning alternative. As a result, the RASM is developed to overcome this challenge.

To apply RASM, the sum of all the weights must equal one, which is in accordance to how the calculation of the weighting matrix is utilized in the regret model. Points are then generated in a vector that would satisfy all the constraints. The decision-maker may apply constraints that can reduce the algorithm's time. As an example, the decision-maker may choose a preference constraint such that the weight for traffic safety must always be larger than that of time of completion. Depending on the confidence level and interval required, a sample size can be determined, which would act as the minimum number of point vectors to be generated for the weights.

Once the weight vectors have been generated that would satisfy a set of constraints, the total scores for all alternatives are then evaluated to generate a regret matrix for each vector and a winning alternative is then associated to each point generated. From a set of different alternatives, a probability can now be associated with each winning alternative due to the variance in the weights.

Presently, not only using the weight matrix for each performance indicator to determine the preference of the decision-maker is important, but also it is offset with an alternative score weight, giving each alternative a weight based on the probabilities determined by the hypothetical alternatives. RASM provides the necessary steps to purge multiple feasible solutions and ensures a single winning alternative for different feasible weight values.

Generally, the overlap measure method is able to handle risky performance indicators for different alternatives, since exact outcomes of design alternatives are uncertain. Hence, a set of outcomes with associated probabilities is the only information present when making selection decisions. The overlap measure method is also able to mitigate the effects of uncertainties that arise due to the risky nature of the performance indicators. The overlap measure method incorporates the use of HEIM as a decision-making tool that allows the decision-maker to make simple choices between pairs of alternatives to gather sufficient data to reach a decision. It ensures a robust winning alternative through RASM, which provides a systematic approach to determine the attribute weights, such that the winning alternative is robust to small changes in the weight values.

Conclusively, the model is sensitive to the probability matrix, which is obtainable through statistical data comparing the model with reality and the probability that the model used for each performance indicator is reliable. On the other hand, once using the HEIM and RASM techniques to view the sensitivity of the weights to the over all model, it is observed

that the results are not sensitive to the weights within a specific confidence level. However, this would only be true if the HEIM and RASM techniques are constrained. In other words, if the decision-maker has prior knowledge of which performance indicator is ranked higher than another, within equality or inequality equations as discussed earlier, but is uncertain of how much higher each attribute is, then the results would still be insensitive to the weights as the outcome would be within the range of the confidence level deeming the difference, if any, insignificant.

Although neither the HEIM nor RASM techniques do not have a limit on the number of performance measures, it is always best not to have too few or too many performance indicators. It is very important to note that this model is not an exact science. Thence, having more data to be more precise is not an accurate statement to make. Also, the values will be more disperse, the more attributes are used. However, the model would still be able to measure the best alternatives, though the probabilities of the insensitivity of the weights may decrease as the decision-maker may not be able to constrain the values correctly.

Since the model permits the decision-maker to devise a ranking strategy based on objectives, the model also allows the addition or subtraction of some performance indicators beyond those suggested in this research. Although the model is insensitive to the weights as long as they are constrained with equality or inequality equations using the HEIM and RASM techniques, it is sensitive to the removal of performance indicators. To remove a performance indicator from affecting the

decision-making in comparing between alternatives, the entire row for the performance indicator can be removed or simply the performance indicator can be given a weight of zero. In such a case, it is very important for the decision-maker to assess which performance indicators need to play a role in the decision-making process beforehand and this also falls within the sensitivity based on the constrain equations of the HEIM and RASM techniques.

As the HEIM and RASM techniques include constraints as to which performance measures are considered equally as important or higher, these constraints also regard whether or not a performance indicator is important, or otherwise, it is given a value of zero in the weighting matrix. However, once the constraints are established, then the weighting values for the remainder of the performance indicators become insensitive. An example for the sensitivity of the model is also illustrated in the next section.

One dilemma zone may still exist if the strategy considered by the decision-maker is itself regretted. For example, it is possible that the decision-maker adopts a strategy that considers traffic flow highly important, while the traffic safety the least important. With such a consideration, this strategy may by itself be regretted.

There is always a possibility for regretting the strategy and a strategy sensitivity matrix may be developed that can determine the amount of regretting the strategy, and not necessarily the regret of the choice of alternative. One method for quantifying the regret of the strategy used is

by evaluating this matrix using a similar principle applied by the RASM technique, in which points are used between constraints for the weights. However, to evaluate the amount of regret of the strategy would consider a completely unconstrained RASM technique in which points are chosen at random for the weights and this time to also include zero weights which would show scenarios if a certain criteria has been completely ignored. All permutations of the weighting strategy would be evaluated and the mean regret for each alternative is computed.

Once the results of a specific strategy are evaluated, the results would be compared to the mean unconstrained regret matrix. A least-mean square is estimated determining which alternative's result is the closest to the mean. If it so happens that the winning alternative is the closest to the mean, then it is understood that the winning alternative is within an indifference zone with respect to the regret of the strategy. This implies that that the winning alternative would be indifferent to the strategy applied, even though it may be sensitive. Nevertheless, the probability of regret is less than the probability of regretting a different alternative, and therefore the winning alternative would still be ranked as the best choice.

If it so happens that the winning alternative of a specific strategy gives a ranking that is completely different than the mean, then a possibility of regretting the strategy exists. An optimization procedure may be utilized to find the best strategy to use based on regression of the results. Optimization of the model is a topic for future research as discussed earlier.

4.7 Working Examples of Regret Theory

Not every theory is practical. Some theories bring more abstraction than they can solve problems. This is not necessarily the goal of this research. A practical approach of the theory is outlined in this section to show the reader the method of bringing the theory discussed in this chapter into practice. A model of values for possible road design alternatives for the initial construction of Dubai interchanges, as discussed in part of the case study, is outlined, although it may be generalized to other examples.

In the case of the construction of the Dubai interchanges, three different alternatives were initially determined as separate selections. The strategy made at the time for the selection criteria is to have an interchange that would provide the best choice for traffic flow to alleviate the congestion, and to complete it as soon as possible, since the congestion problem had been so great that it was impeding the economic growth of the city.

Planning issues and traffic safety ranked in mid-priority in the selection criteria, as the interchanges were needed to increase the valuation of the land around and to incite the economy of the area. Traffic safety was not as important in the selection criteria as the traffic flow, as the major concern at the time was the alleviation of the congestion, and not because there were too many traffic crashes at the time, especially since the interchanges used to be roundabouts that held an excellent record in traffic safety.

Though may be surprising, the cost of construction was ranked the lowest in the selection criteria strategy, as the city needed to do improvements on the highway as quick as possible and to the best as possible, no matter at what cost.

The first alternative was the largest design of all with huge traffic capacity and provided the best score for the planning performance indicator, since the valuation of the land would be the highest as it allowed for great growth alongside the highway, as it also had the best score for traffic flow.

Alternative one, however, did not score well with traffic safety. Due to its high capacity, the speeds of the vehicles along the ramps were designed for high speeds, though the numbers of conflict points were not significantly different, as compared to alternative two. Conversely, due to the large capacity and vastness of the interchange, it costs more at around $80M per interchange, and the time of completion was high as well, due to demolition work that would be required alongside the interchanges to make room for construction, especially within expedited conditions.

The first alternative would take about eight years to complete for the repurchasing and demolition work to begin, and the actual construction to start and complete. The cost of the project was maintained at low levels as the resources required for the completion of the project were dispersed over many years making it cheaper form having all resources available at once, as in the other alternatives. It is not a design-build

project, which is more of a reason that made this project time-consuming. Since time was given a high importance in this project, it seemed unlikely for this alternative to be a winner.

The second alternative scored great in cost and time of completion, as it neither required much of repurchasing lands around the interchange nor any demolition would be required. The cost of the second alternative was at around $50M, as part of the cost was given for an expedited construction to be completed in about one year only. Also, the second alternative would have been compact compared to other alternatives allowing for cheaper and quicker construction. Nonetheless, it scored the lowest compared to other alternatives in planning and traffic flow performance indicators, since the interchanges would somewhat restrict the growth of the lands around it in terms of zoning. In regards to traffic safety, the second alternative scored better than the first. Though it carried about the same number of conflicts, the design speeds of the ramps were lower, allowing for safer traverse of vehicles along the interchange.

The third alternative scored best in traffic safety, as the design was an elevated roundabout, allowing for safer conflict point types and lower speeds at ramps. Otherwise it scored moderately compared to other alternatives, as if it were the middle choice. The time of completion was also not too significantly different than the second alternative, because it was to be built without any requirement for demolition of any surrounding buildings as well, which also saved on higher costs. The time of

completion was mainly few months more than the second alternative costing at around $65M.

Normalizing the performance indicators are important as discussed earlier. Looking at the three different alternatives for a road design, and by using different models to obtain the normalized performance indicators for each of planning, traffic flow, traffic safety, construction economics, and time of completion respectively, the following matrix is obtained as shown in *Table 4.4*:

Table 4.4 Performance indicator matrix

			Performance Indicator Matrix		
		W	**a_1**	**a_2**	**a_3**
Planning Objectives	**PI_1**	3	0.7	0.3	0.5
Traffic Flow	**PI_2**	5	0.9	0.5	0.7
Traffic Safety	**PI_3**	3	0.4	0.5	0.6
Project Cost	**PI_4**	1	0.5	0.7	0.6
Time of Completion	**PI_5**	5	0.1	0.9	0.8
		17	**0.520**	**0.580**	**0.640**

Each performance indicator is given a weight that would signify the relative importance of each performance indicator against another, in accordance to the selection strategy criteria determined, reflecting the preference of the decision maker(s). Later in this example, it will be shown how the model is sensitive if the weights are not constrained to a strategy, but insensitive if the weights are constrained within a strategy determined by the decision-maker. The loss matrix is calculated based upon the maximum known loss compared to other alternatives as shown in *Table 4.5*:

Table 4.5 Loss matrix

			Loss Matrix		
		W	a_1	a_2	a_3
Planning Objectives	PI_1	3	0	0.4	0.2
Traffic Flow	PI_2	5	0	0.4	0.2
Traffic Safety	PI_3	3	0.2	0.1	0
Project Cost	PI_4	1	0.2	0	0.1
Time of Completion	PI_5	5	0.8	0	0.1
		17	**0.240**	**0.180**	**0.120**

According to the Loss Matrix, in *Table 4.5*, it appears that the third alternative is the best in this case with the minimum overall loss. Nevertheless, the probability of certainty provides an insight of the level of certainty contained, in which its inverse provides the level of uncertainty.

The probability matrix provides the quantitative confidence level of certainty for each performance indicator of every alternative. Although for the majority of the cases, the probability may be similar to each performance indicator, since the same model is used to compare different alternatives, it may not always be the case. It is possible that the probability within the same model be evaluated differently for different road designs, depending on the geometric parameters of the road, the type of intersection, the progression of traffic along network links, or the network connectivity. This may be true for all performance measures used, as models for each of the performance indicators may be more reliable and accurate to some of the road designs and less reliable to others.

As an example, a model may give better certainty for values obtained in analyzing the traffic flow of intersections than roundabouts. Theoretically, it is possible to use different models when analyzing different alternatives. However, this would create some bias in the values obtained and therefore, would not give a fair comparison between all the alternatives. Hence, consistency is critical. In this example, it is assumed that the probabilities of each performance indicator is perfectly uniform, as shown in *Table 4.6*, and compare it to another where the probabilities are not perfectly uniform.

Table 4.6 Probability matrix

		Probability Matrix		
		a_1	**a_2**	**a_3**
Planning Objectives	**PI_1**	0.75	0.75	0.75
Traffic Flow	**PI_2**	0.9	0.9	0.9
Traffic Safety	**PI_3**	0.8	0.8	0.8
Project Cost	**PI_4**	0.85	0.85	0.85
Time of Completion	**PI_5**	0.7	0.7	0.7
		0.800	**0.800**	**0.800**

Given the loss matrix, the probability matrix, and the weight given to each performance indicator, the regret matrix is evaluated, as previously stated, using the formula in *Eq. 4.8*:

$$R_{ij} = w_{ij} \cdot (1 - P_{ij}) \cdot (L_{ij}).$$

Therefore, the regret matrix, as shown in *Table 4.7*, is evaluated giving the same results as the loss matrix, with the minimum regret equivalent to the minimum loss.

Table 4.7 Regret matrix

		Regret Matrix		
		a_1	a_2	a_3
Planning Objectives	**PI_1**	0	0.3	0.15
Traffic Flow	**PI_2**	0	0.2	0.1
Traffic Safety	**PI_3**	0.12	0.06	0
Project Cost	**PI_4**	0.03	0	0.015
Time of Completion	**PI_5**	1.2	0	0.15
		1.35	**0.56**	**0.415**

However, it is important to note that if it is assumed that the probability matrix is not uniform, then the regret matrix may not necessarily give the same results as the loss matrix. If the probability matrix is modified, then the regret matrix changes in direct proportion to it.

For example, if Alternative 3 is an evaluation of a roundabout, and the model used provides less certainty, 70%, compared to the evaluation of an intersection, 90%, then the probability matrix, as shown in *Table 4.8*, would change the final results of the regret matrix, as shown in *Table 4.9*.

Table 4.8 Modified probability matrix

		Probability Matrix		
		a_1	a_2	a_3
Planning Objectives	**PI_1**	0.75	0.75	0.75
Traffic Flow	**PI_2**	0.9	0.9	0.7
Traffic Safety	**PI_3**	0.8	0.8	0.8
Project Cost	**PI_4**	0.85	0.85	0.85
Time of Completion	**PI_5**	0.7	0.7	0.7
		0.800	**0.800**	**0.760**

Now it can be seen that the minimum regret does not necessarily coincide with the minimum loss, based on a probabilistic approach.

Table 4.9 Modified regret matrix

		Regret Matrix		
		a_1	a_2	a_3
Planning Objectives	**PI_1**	0	0.3	0.15
Traffic Flow	**PI_2**	0	0.2	0.3
Traffic Safety	**PI_3**	0.12	0.06	0
Project Cost	**PI_4**	0.03	0	0.015
Time of Completion	**PI_5**	1.2	0	0.15
		1.35	**0.56**	**0.615**

Since the probability matrix has been changed, the regret matrix effectively provides with different values, and therefore a possibility for a different solution for the best alternative. In the above example, the second alternative is found to be the best alternative. This is due to the fact that more certainty exists with the values provided by first and second alternatives, than we are with the third. Meaning, that though the third alternative would provide the minimum loss, the amount of uncertainty in such values is higher, giving a higher risk to trust such values and consequently, the amount of regret is higher, since regret and certainty are in direct proportion.

4.8 Working Examples on Sensitivity of Weights

From the example in the previous section, a strategy has already been established in determining the best alternative, in which the weights have directly influenced the results. However, determining weights are very subjective, and thus, how the decision-maker(s) utilize it would directly affect the outcome. It is, therefore, important to evaluate a sensitivity analysis of the results. As discussed earlier in the study, the

RASM technique may be used to lessen the effects of weights on the outcome.

If it is assumed that the decision-making process has no established strategy as to which performance indicator is ranked higher above others, which would also mean there are no inequality constraints using the HEIM technique, as part of the RASM methodology, then it is assumed that all indicators have equal weights in accordance to the principle of indifference, otherwise known as the principle of insufficient reason.

Looking at the previous example, Table 4.9 would give different results if each performance indicator is given an equal weight of unity, as shown in Table 4.10. The results show that the third alternative holds the least regret, instead of the second alternative as in Table 4.9. However, it is also noted that the difference between both the second and third alternatives is about 3.125%, which is within the range of the confidence level, and therefore, in reality, the results do not show any significant winning alternative between the second and third options.

Table 4.10 Same weight regret matrix

		Regret Matrix		
		a_1	**a_2**	**a_3**
Planning Objectives	**PI_1**	0	0.1	0.05
Traffic Flow	**PI_2**	0	0.04	0.06
Traffic Safety	**PI_3**	0.04	0.02	0
Project Cost	**PI_4**	0.03	0	0.015
Time of Completion	**PI_5**	0.24	0	0.03
		0.31	**0.16**	**0.155**

Considering that the decision-maker has at least a ranking strategy, as measured in the previous section, where the performance indicators for traffic flow and time of completion are regarded equally high, planning and safety are ranked equally moderate, and cost is regarded the lowest, but if it is not known how different is one ranking to another, such as how much higher is traffic flow regarded to safety, then using the RASM method may be appropriate to decrease the amount of sensitivity within the final results.

A ranking strategy is very important to be identified early in the study by the decision-makers. Assuming a scale from 1 – 5, 1 being lowest in rank and 5 being highest in rank, then it can be attempted to give the performance indicators the following ranking permutations as shown in Table 4.11.

Table 4.11 Weighting permutations

		Weighting Permutations								
		W_1	W_2	W_3	W_4	W_5	W_6	W_7	W_8	W_9
Planning Objectives	PI_1	3	2	2	2	3	4	3	3	4
Traffic Flow	PI_2	5	3	4	5	4	5	4	5	5
Traffic Safety	PI_3	3	2	2	2	3	4	3	3	4
Project Cost	PI_4	1	1	1	1	1	1	2	2	2
Time of Completion	PI_5	5	3	4	5	4	5	4	5	5
		17	**11**	**13**	**15**	**15**	**19**	**16**	**18**	**20**

The first weighting strategy, W_1, is the same as initially implemented in the example. The second weighting strategy gives alternative two the winning advantage over the third alternative with a difference of about 6.5% in the regret results, which may be considered statistically significant. The results of the permutations are seen in Table 4.12.

All permutations show a competition between the second and third alternatives, where the first alternative is clearly beyond any winning range, and therefore, may be ignored in identifying the final winning alternative. The winning alternative is highlighted for each weighting permutation in Table 4.12.

Table 4.12 Weighting permutation results

	Permutation Results		
	a_2	**a_3**	**%Difference**
W_1	0.56	0.615	8.94%
W_2	0.36	0.385	6.49%
W_3	0.4	0.475	15.79%
W_4	0.44	0.565	22.12%
W_5	0.52	0.525	0.95%
W_6	0.68	0.665	2.26%
W_7	0.52	0.54	3.70%
W_8	0.56	0.63	11.11%
W_9	0.68	0.68	0.00%

Clearly from the above table, the second alternative is a winner in most permutations. In the cases that the third alternative turns out to be a winner, the percent difference is very small deeming it insignificant within a chosen confidence level. In some permutations, the second alternative is by far the winner. According to the RASM technique, the second alternative would therefore be the winner, without competition.

Considering the first scenario in the working example, where the probability matrix is unmodified, then the third alternative is undoubtedly the winner without competition as can be evidently seen in Table 4.13.

Table 4.13 Weighting permutation results for first case scenario

	Permutation Results		
	a_2	a_3	%Difference
W_1	0.56	0.415	34.94%
W_2	0.36	0.265	35.85%
W_3	0.4	0.315	26.98%
W_4	0.44	0.365	20.55%
W_5	0.52	0.365	42.47%
W_6	0.68	0.465	46.24%
W_7	0.52	0.38	36.84%
W_8	0.56	0.43	30.23%
W_9	0.68	0.48	41.67%

Thence, it can be concluded that if using the RASM technique, it becomes technically palpable that the weighting system of the regret matrix is not highly sensitive to the weights as much as the probability matrix. However, this statement is only true if the weights are constrained. In other words, the strategies are known as to how they are ranked from each other, even if how much greater is the ranking of one performance indicator to the other is uncertain.

If the weighting matrix has been reversed, giving the lowest performance indicator the highest value and vice-versa, then the outcome give interesting results as shown in Table 4.14.

Table 4.14 Reversed weights regret matrix

			Regret Matrix		
		W	a_1	a_2	a_3
Planning Objectives	PI_1	3	0	0.3	0.15
Traffic Flow	PI_2	1	0	0.04	0.06
Traffic Safety	PI_3	3	0.12	0.06	0
Project Cost	PI_4	5	0.15	0	0.075
Time of Completion	PI_5	1	0.24	0	0.03
		13	**0.51**	**0.4**	**0.315**

Noticeably, the first alternative is not a winner in this case either. Since the first alternative is the best in planning and traffic flow performance indicators, it would easily become a winner if the strategy used considers those two measures highly. It is therefore concluded that if the weighting matrix is not constrained, and the weights are placed randomly, then the reliability of the results would be dubious. Hence, it is important, as noted earlier, that a strategy must be formed declaring how performance measures are ranked against each other, even if the ranking level is uncertain, as it would be taken care of using the RASM technique to ensure that only one alternative is the winner, regardless of the weights. Thus, constraints for the equations must exist, as proposed by Gurnani et al. (2003) and Gurnani and Lewis (2005).

Since the results of the regret matrix are not sensitive to the weights, once the weighting matrix has been constrained by a strategy, it is sensitive if the weighting measurements are unconstrained. Using the same logic, removing certain performance measures from the regret matrix will directly affect the outcome. Therefore, it is crucial for the decision-makers to choose a strategy beforehand to ensure the reliability of the results.

From the previous example, assuming that the time of completion is not only unimportant, but also inconsequential to the decision-making process, and therefore ignored in the regret matrix, given a nil weight, then the matrix will give completely different results as shown in Table 4.15.

Table 4.15 Regret matrix after ignoring time of completion

		W	Regret Matrix a_1	a_2	a_3
Planning Objectives	**PI_1**	3	0	0.3	0.15
Traffic Flow	**PI_2**	5	0	0.2	0.3
Traffic Safety	**PI_3**	3	0.12	0.06	0
Project Cost	**PI_4**	1	0.03	0	0.015
Time of Completion	**PI_5**	0	0	0	0
		12	**0.15**	**0.56**	**0.465**

It becomes clear from the above results that the first alternative will by far become the best alternative, if the time of completion is completely ignored by the decision-makers, in accordance to the strategy developed. It is obvious that the time of completion was of great importance in the previous example, and since the first alternative takes about eight years to complete as compared to the others which only take a little over a year to complete, then it is almost always dominated by the other two alternatives. However, if the performance indicator for the time of completion is ignored, then the first design becomes a clear winning alternative. Consequently, it is fundamental for the decision-maker to incorporate a strategy of what performance indicators need to be utilized to compare between alternatives. It is this strategy that will determine the constraints of the RASM technique that will ensure only one winning alternative would pass, even if how much one performance indicator is more important than the other would be uncertain or subjective.

Generally, the sensitivity of the model to the weighting matrix is insignificant as long as constraints exist when considering the RASM

technique. Those constraints are subject to the strategy developed by the decision-maker prior to the evaluation.

4.9 Fuzzy Logic in Decision Theory

Fuzzy theory represents vagueness. Vagueness, however, is different from randomness. Unwin (1986) has emphasized the distinction between two forms of uncertainty that arise in risk and reliability analysis, i) uncertainty due to randomness inherent in the system, and ii) uncertainty due to the vagueness inherent in the assessor's perception and judgment of that system. Unwin (1986) proposes the use of a probabilistic approach to evaluate the uncertainty due to randomness. Whereas fuzzy set theory provides a formal framework for the representation of vagueness. In fuzzy decision theory, uncertainty about probability is taken to be a form of fuzzy vagueness rather than a form of stochastic probability (Dubois and Prade 1988). Fuzziness is a non-statistical concept. Therefore, the laws of probabilities would not apply in the laws of fuzzy membership.

One of the reasonable operations of fuzzy set membership is the intersection operation. Since each performance indicator has a range, members that intersect can be considered as similar. Thence, members that belong to the same fuzzy, though can be ranked against each other, their similarities need to be highlighted, as the difference between them would not be statistically significant.

A good decision has to satisfy both goals and constraints (Bellman and Zadeh 1970). However, Bellman and Zadeh (1970) have applied fuzzy

values to goals and constraints impartially from one another, considering a non-weighted approach. In this research, since each of the performance indicators are weighted according to the importance appropriated by the decision-maker, it is imperative to have an understanding of how this weighting would affect the fuzzy set.

If a performance indicator has a high weight, then it is necessary to ensure that an alternative would not belong to the solution set that would have a small membership value. To accomplish this, membership values to the decision fuzzy set is given in proportion to the weight of each performance indicator. Yager (1976) has considered this concept, when the usage of exponential weighting to accomplish this differential weighting has been established.

Generally, since the performance indicators are numeric and can only approximate the real state of nature, they may be represented as fuzzy numbers and a calculated fuzzy expected utility is applied. Thence a regret approach, as discussed earlier, would still be able to represent the uncertainty factors within fuzzy sets and ensure that the action taken would be for the alternative with the least regret factor, applying the same method as described in Section 4.4.

4.10 Critique of Decision Theory

Understanding situations that cause decision-making strategies is a complex procedure. In many ways, the decision-making process may be affected indirectly by unrelated events. Imagine the following sequence of events:

1. You have an important meeting at work.
2. After you wake up and by the time you are drinking your coffee, you spill your coffee onto your shirt.
3. You try to change your shirt, finding out that you do not have a clean shirt to wear.
4. You try to find something to wear and later decide to wear yesterday's shirt, though unclean, still cleaner than the shirt stained by the coffee.
5. As you go into your car, you realize that you forgot the car keys in your apartment and you are locked out.
6. You always keep a spare hidden outside, but realized you gave it to your spouse the day earlier to replace a lost key.
7. Your neighbour is retired and rarely ever uses the car, so you request to borrow the car. You find out that his engine has failed the day earlier and it has not been fixed yet.
8. You try to use the bus, but the public transport employees are on strike today.
9. You call for a cab, but none is available as many people are requesting them due to the strike.
10. You call your work informing them that you cannot make it to the meeting and request your colleague to represent you in the meeting instead.
11. Your colleague is not well prepared and is not experienced enough. Therefore your colleague's input is not effective and the wrong decision is made.

Who or what is to blame in this situation of sequence of events that led to the final decision? Is human error to blame for spilling the coffee in the first place or forgetting the keys? Is mechanical error to blame due to the neighbour's car not working? Is the environment to blame by having bus drivers on strike or taxi cabs overloaded with requests? Is the design of the system to be blamed for locking you out? Is the procedure incorrect, by drinking coffee before leaving the house? Is the schedule timing to be blamed?

Life is complicated. Therefore, decision-making is a complex system. Similarly, looking into decisions pertaining road design alternatives can be as complex as decisions to go to a meeting. The decision can only be perfect, if all the assumptions are perfect. If the inputs of our decisions are correct, only then can decisions be made as such.

However, it is acknowledged that assumptions cannot be as perfect as they are liked to be. Hence, in decision-theory, not only probabilities based on assumptions are looked at, but also factor in regrets. Yet, regret factors are assumptions themselves. There is no way to get a perfect system using a more deterministic method than using stochastic assumptions.

A complex system exhibits complex interactions when it has:

1. Unexpected sequences which are not immediately understood.
2. Design features such as branching, feedback loops.
3. Opportunities for failures to jump across subsystem boundaries.

A complex system is tightly coupled when it has:

1. Time-dependent processes which cannot wait.
2. Tightly ordered sequential processes (bus drivers on strike → taxis overloaded).
3. Only one path to a successful outcome (failure to have backup).
4. Limited time or resources (requiring precise quantities of resources for successful operations).

Subsystem linkage and interaction between different factors is very important when analyzing decision-making strategies. It is easy to imagine that there exists a linkage between keys and a car, but not between an unclean shirt with a car. Similarly, when traffic accidents are looked at, there are many factors that would cause them.

Just like a chess game, what is the probability that two chess games played in the world will have exactly the same moves from start to end? A chess game is a sequence of moves, which are sometimes related, and other times not related at all. For example, it may be necessary to move the pawn to give way for the bishop to move. However, at some point in time, in the middle of the game, would it have been necessary to move the bishop to move the knight? The sequence of events that lead to wrong decisions can also be as complex as a chess game. How many accidents in the world have similar sequence of events? Thus, in this research, how could it be determined whether or not the road design is the best if an alternative has not been tested? The process, though objective-driven, is in itself subjective, and therefore its dependability is under threat.

Let us imagine a possible sequence of events leading to an accident:

1. A person wakes up late in the morning and tries to rush to work.
2. Due to the rush, the person decides not to have coffee and grab a sandwich to be eaten in the car.
3. The person drives and speeds up in the road trying to weave between cars to get through as quick as possible.
4. Because the person did not have coffee, the person was dozing off while driving.
5. As a fire truck is about to pass in the crossing street, the traffic signal unexpectedly changes to red, but by the time the sleepy driver realizes that the signal has changed, the driver tries to hit the brakes as the car in front attempts to stop, respecting the traffic light.
6. Apparently, the brakes are not functioning properly in the car.
7. Though the adjacent lane is empty, the driver could not turn the wheels, as the right hand is still grabbing hold of the sandwich.
8. CRASH!

How would this accident be avoided?

1. The driver should have slept early to wake up early?
2. The driver should have drunk coffee (and coming late to work)?
3. The driver should not have been eating a sandwich?
4. The braking system should have been checked before driving?
5. The fire truck should not have come, changing the traffic signal?

Analyzing each question:

- The driver should have slept early to wake up early.

If this was the case, the brakes, would still have failed in this situation, and an accident might not have been avoided.

- The driver should have drunk coffee.

The brakes would still not be functioning properly, and therefore, this accident might not have been avoided even by driving wide awake.

- The driver should not have been eating a sandwich.

Even so, the driver might have been able to turn the wheels to the next lane. Since the brakes do not work, the car might have drove onto the intersection as cars from the crossing road drive through, still getting into a different, and probably a more serious accident, which would have even delayed the fire truck to pass responding to a different emergency.

- The driver should have checked the brakes before driving.

If the driver has checked the brakes, and everything was fine, because the driver was dozing off and driving fast, the driver might not have responded to the sudden change in the traffic signal on time, and therefore, still have the accident.

- The fire truck should not have come, changing the traffic signal.

With all other factors, if the accident did not occur in this intersection, it would eventually come in others.

Now that each possible cause of the accident is evaluated, if each cause is given a fair trial, the defense attorney will have eloquent arguments to judge each cause innocent of the consequential event. Who is to blame for the accident? How would it even be started to identify what the decision must have been to avoid the accident?

An accident is defined as a sudden, unexpected, unplanned, and an unintended event. However, if it is attempted to trace the cause of such an event, the trace will always return empty handed. How then, can a decision be made about a cause which cannot be proven? For this reason, decision-theory will be as limited as the assumptions made. Therefore, although decision-theory might be a useful analysis tool for accidents and determining the authenticity of the decision made, it would not replace a professional judgment of traffic engineers.

Therefore, the performance indicators and the regret matrix, as defined earlier, might be due to assumptions, and thus the reliability of this regret is at stake. Thence, the decision path that has been concluded in this study would only be as good as the confidence level of the probabilities evaluated.

5. Developing a Planning GIS Decision Model

5.1 Introduction

Decision-making for urban planning is generally multi-criteria in its nature. Different inputs are usually conflicting. To have the best revenue for the economy would mean to use land for high rise mix use. However, the placement of facilities, such as schools, police and fire stations are also necessary. The need to place houses of worship, such as churches, would also be necessary in the planning to serve the community. Therefore, finding an optimal criterion is not as simple as one might imagine. From Chapter 3, it has been determined the different inputs for a GIS planning model that would serve as an optimization tool for reaching different objectives set by the planner or decision-maker.

Urban planning GIS models are important to i) take into consideration the multi-criteria nature of planning decision-making, ii) centralize and interact between various stakeholders in the planning process collaboratively (Healey 1997), and iii) provide communication between experts and local communities (Innes 1995, Healey 1992).

Different large-scale models have been proposed to support spatial decision systems in urban planning, especially for transportation planning (Batty and Xie 1994a). Most of them have been developed for operational research and economics, such as linear programming, optimization techniques, and cost-benefit analysis. Lee (1973) has identified some limitations that these models hold and concluded that

most models would have at least one of the following limitations: they i) do not represent the complexity of spatial problems to decision-makers, ii) neglect social qualitative and other critical interactive dimensions, iii) neglect spatial dynamics, and iv) do not support communicative and collaborative decision-making.

When evaluating between different road designs, both a large-scale and a small-scale assessments are necessary. The large-scale model determines the overall effect the new road design has on the traffic network and the overall consequences to the planning of the area. Once an alternative passes the large scale model, then a small scale model is used. Therefore the large scale model acts as a filter. As a design alternative passes the large scale model, then the processes to run a small scale model starts. The method ensures that processing time is not wasted on alternatives that would not pass anyways, due to the large scale model.

Land is the most valuable asset to any community. It is the sole physical restriction for any kind of development to an urban area. Managing the land would determine the ability for the urban area to grow socio-economically and even the development of the human residing within the area. Besides financial restrictions, the ability to develop schools, universities, industries, commerce, etc that would help the growth of any urban area is limited to the availability of land and how the land use is planned.

An urban city and a human body have a lot in common. The human body is spatially planned to allocate different organs and networks, such as the circulatory and endocrine networks in an optimized method such that the body can self-sustain. It has the capability to place critical defense mechanisms in strategic places while at the same time continues to process energy and feed the body with nutrients in a highly optimal method. Development and services in the human body move hand in hand. Although the human body starts to grow in the beginning, the relative spatial positions of networks and organs remain comparatively the same. This is similar to the development of an urban city.

5.2 Decision Map

According to Chakhar et. al. (2005), a decision map is constructed to identify the multi-criteria decision-making process in urban planning. The definition provided by Chakhar et. al. is as follows:

Definition. A decision map M is defined as $\{(u, f(u)) : u \in \mathrm{U}\}$, where U is a set of homogenous spatial units (or zones) and *f* is a function defined as follows:

$$f : \mathrm{U} \rightarrow E$$
$$u \rightarrow f(u) = \Phi[g_1(u), \ldots, g_m(u)]$$

where *E* is an ordinal scale, Φ is a multicriteria aggregation model and $g_i(u)$ is the performance of spatial unit *u* according to criterion g_i.

The purpose of the decision map is to summarize the preferential information of the decision-maker with respect to a set of conflicting evaluation criteria into an ordinal information. The criteria may represent physical data, such as slope, or non-physical, such as vulnerability to pollution. Each criterion is represented as a thematic map composed of a set of homogenous spatial units. For each of the spatial units an ordinal or cardinal evaluation is associated with it relatively to a scale *E*. The construction of a decision map requires the aggregation of the different criteria maps into one final map that looks like a set of homogenous spatial units; each one is characterized with a global, often ordinal but it can be cardinal, evaluation that represents an aggregation of several partial evaluations relative to different criteria.

5.2.1 Gathering Information for the GIS model

Each criterion map must represent a specific theme, whether a natural phenomena, such as water bodies, or not. The criterion map may be extracted from the data stored in the GIS through a series of simple transformations (e.g. reclassification, interpolation). For example, a criterion map representing the slope may be obtained from the Digital Elevation Model (DEM). The definition of criterion maps of non real phenomena calls for more complex models and requires often the intervention of the analyst/expert to model the considered phenomena. Modelling may simply take the form of some additional information to incorporate into an existing data layer, or, often, to the creation of a new data layer. In this last case, the definition of the criterion map requires an overlay of several data layers. For instance, a criterion map of "aptitude to urbanization" is obtained through the overlay of several data layers

representing the following information: slope, lithology, wetland, overflowing and landslide.

A criterion map could incorporate also experiential knowledge of local communities. It is an important element in structuring and representing the decision context that decision maker has to tackle. Aspirations, beliefs, preference and value systems of local communities can support decision makers in the decision process, preventing potential conflicts.

Once the criterion map is generated, it is composed of a set of homogenous spatial units each one is characterized with one evaluation according to an ordinal or cardinal scale *E*. In practice, criteria are often of different types and may be evaluated according to different scales.

The next step consists in generating an intermediate map through the intersection of the criteria maps. The generated intermediate map is composed of a new set of spatial units which result from the intersection of the boundaries of the spatial units of the different criteria maps. Each spatial unit is characterized with a vector of m evaluations relative to the m criteria.

Formally, to each spatial unit u, it is associated to the vector $[g_1(u), g_2(u),\ldots,g_m(u)]$. To be able to perform the overlay operation, different criteria maps must represent the same territory and must be defined according to the same spatial scale and the same coordinate system.

To generate a final decision map, it should first use an aggregation mechanism to aggregate the vector associated with each spatial unit u in the intermediate map into one global evaluation.

Mathematically, it is represented as:

$$g(u) = \Phi[g_j(u)]_{j \in F}.$$

F is the criteria family and Φ is the aggregation mechanism defined by Chakhar et. al. (2005) as follows:

$$\begin{array}{l} \Phi : E^m \rightarrow E \\ [g_1(u), g_2(u), \ldots, g_m(u)] \rightarrow \Phi(u) \end{array}.$$

Through the decision map, potential alternatives are evaluated. In this research, it is assumed that everything is fixed and the only dynamic data are the potential alignments of the road under study. Hence, the difference is how the lines representing the road consider different alignments.

5.2.2 Land Use Model

Several criteria for planning and land use are required. A basket of different data is necessary for a broad evaluation of land use planning and the valuation of properties. As discussed in Chapter 3, there are necessary planning data that are important.

To understand land use, the availability of land is necessary. If the road under construction is within a fully developed area, in which the purpose is widening the existing road, for example, or redesigning an intersection, then the land use surrounding the area would have already been determined. Therefore, there are not many unknown variables. However, if the road is being constructed in a partially developed or a rural area, then there are several unknown variables that need to be considered.

To understand the impact of a road design to the land use in an area, it is essential to determine the buildable areas from the total land supply. The buildable land supply are divided into three categories, i) vacant, ii) partially utilized, and iii) under-utilized. Those categories are considered the land supply available. They are usually restricted by government regulations, such as zoning, which mainly decides on the capacity.

If a land is vacant, then it is important to understand its potential and determining its capacity. Computing the capacity of infill for partially developed lands is also important and understanding the potential land uses as well. However, determining the potentials of partially developed lands is restricted due to the already existing land use and public facilities. On the other hand, under-utilized lands, usually, have land uses already determined and therefore it is a matter of understanding the redevelopment capacity of the area. Nevertheless, the land use is known, mainly because a zoning has been established already. However, environmental factors may constrict the capacity of the supply.

The existence of conservation zones, natural slope and geomorphology may also be restrictive in development of the land.

There are socio-economic factors that determine the need of the market that would also determine the capacity of the buildable areas. For example, there might be a market need for more industrial areas or more commercial areas, and therefore, the land use would be determined by such. There might be community needs for public facilities, such as parks, schools, or even places of worship. A summary is illustrated in *Fig. 5.1*.

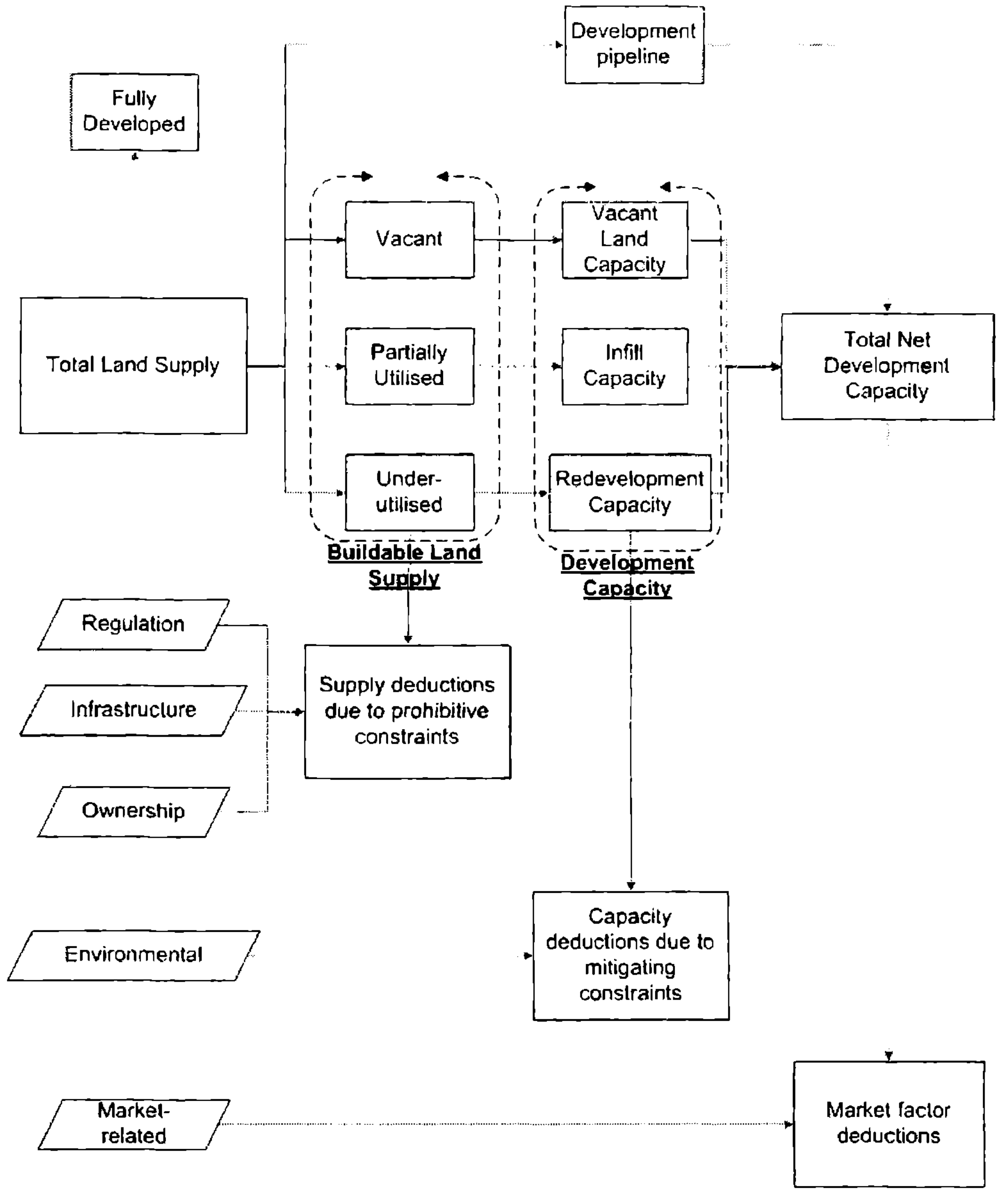

Figure 5.1 LAND USE CAPACITY ANALYSIS

From this analysis, the capacity of the buildable area is determined. This capacity is determined in two variables, a social and an economic. The number of people who live, and the number of people who work in the area determine the social variable. Since it may not be a fair comparison between residential and commercial zones, the social variable is therefore determined by the average annual daily population of the area. This is in comparison to that of traffic. The more people live, work, shop, study, etc, within an area, the more socially valuable it is. Also, the more need for transportation infrastructure would be necessary as well.

Economically, the value of land use is determined, by the physical land value and the income generated. It is not easy to evaluate the income generated from a particular land. For example, spatially, a lake may generate no income, especially if the water is neither used for drinking nor irrigation. However, it is a fact that the existence of such water bodies may increase the value of the lands surrounding it for having a lake-view. Hence, such water bodies, though may generate no direct income, are a major factor for an added-value of the land use around it.

Thence, it is tricky to evaluate the economics of land. However, just as the social variable is not determined by each piece of land in an area, but as a community, similarly, the same is to be determined economically. A lake surrounded by houses is probably valued more than a lake without any planning around it. Similarly, it may be valued less than a lake surrounded by hotel resorts. Hence, it is the community, and possibly a full self-sustaining administrative division that is more important than analyzing each piece of land individually. Thus, from an

economic perspective, the land value and generated income are important. Nonetheless, generated income and land value are somewhat related to each other. It cannot be said, for example, that the land on which the headquarters of a major corporation is located is valued more than its neighbouring property occupied by a less impressive company due to the fact of the global sales the corporation is achieving. Thus, the generated income is more related to the land valuation. A piece of land occupied by a resort and another occupied by a private villa are not immediately priced the same. The generated income of the resort is far more than a private villa. Consequently, the land value of the resort is far more than a private villa. Therefore, the land value would be a good comparison criterion.

As a result, when understanding the best road construction design, what is more important is to understand how to optimize both social and economic factors. A ratio is assessed between the land value and the average annual daily population.

5.2.3 Land Economics

Roads construction has an interesting impact in land economics. Since transportation networks are the bloodstream for any urban city, the more transportation connectivity an area has, the higher the value it gets due to its attraction to commerce. However, land use directly influences the economics of land. Building a highway that connects between business districts will increase the land value of such districts. However, building a highway that passes through low residential areas may have a negative impact.

Nevertheless, as roads are constructed or widened, this increases the Right-of-Way (ROW) and therefore, decreases the land area available. *Fig. 5.2* illustrates the model flow of how supply and demand affects the valuation of parcels according to its land use.

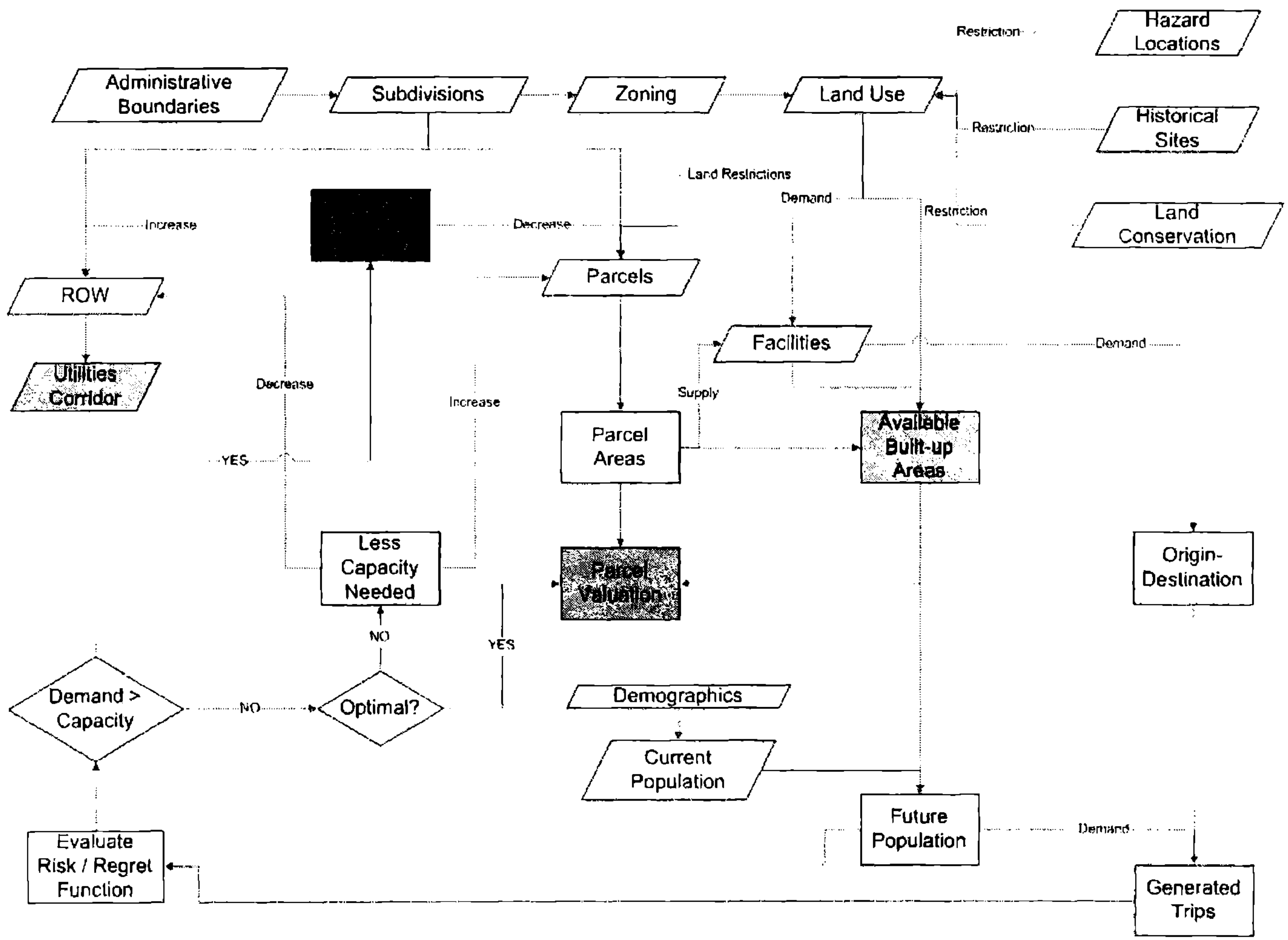

Figure 5.2 PARCEL VALUATION DUE TO SUPPLY / DEMAND

The GIS data necessary for this model includes Administrative Boundaries, in which subdivisions and zoning regulations are extracted. From the zoning regulations, the land use is determined. Land use valuation is directly impacted by transportation networks (Moore and Throsnes 1994).

Restrictions to land development include hazard locations, historical sites, land conservation, etc. Those restrictions determine the scope of the land use, and therefore determine the supply as well as parcel valuation factor. Parcel areas determine the supply available. In any sustainable community, public facilities are necessary, such as hospitals, schools, places of worship, etc. Therefore, if that amount is subtracted from the parcel areas, the availability of the built-up areas is determined.

The land use, including facilities, is a factor for evaluating trip generations from origin and destination analysis. Demographic data is also as important to understand the growth of traffic in an area.

If the demand is greater than the capacity, then a higher capacity need to be achieved, and therefore, the Right-of-Way (ROW) may need to be increased. Thus, the utilities corridor might need to be shifted and even widens to ensure higher capacity for the services, such as water, electricity, etc. Consequently, the parcel areas are decreased to increase the ROW.

When looking at it financially, increasing the Right-of-Way (ROW) may mean that the government needs to compensate private land parcels or

even buy buildings for demolition. *Fig. 5.3* exemplifies how loss is evaluated due to compensations and land valuations due to the increase in Right-of-Way (ROW).

Parcels may have restrictions and therefore their areas may not be reduced. For example, if the adjacent parcel to a current ROW is a historical site which might be protected by law, then the ROW may not be capable for any increase. Thus, this alternative would not be feasible and consequently, another alternative needs to be evaluated instead. Otherwise, the remaining parcel areas are re-valued in accordance to the decrease in its areas, but may increase in its value due to the capability of re-valuating commercial areas since higher transportation capacity is increased. The difference between those determines the loss or increase in parcel valuation for the area.

If increasing the ROW would affect existing buildings, then the evaluation of the purchasing and demolishing the buildings would be important. From buildings data, the building condition is established and the building price is assessed based on its built-up area and how that would adversely affect the population and trips generated.

Once the building compensation and demolition is determined, it is added with the parcel compensation to evaluate the total cost of compensation. However, since the demographics may now be different due to reduced potential development space, and therefore less capacity is required, then the system checks whether or not it has reached an optimal solution. If not, then the algorithm continues until an optimal solution is found.

In a similar situation, the environmental impact due to the increase in the ROW is also necessary to consider for any kind of mitigation costs. The impact on the environment is not necessarily due to physically increasing the area of the ROW, but it is mainly due to the impact on the surrounding environment from gas emissions, ground water quality, clearing of forestry, endangering wild habitat, etc.

Within a GIS context, if the ROW polygon overlaps existing environmental layers with a certain buffer zone, then an understanding of how the environment is affected gets understood. Nonetheless, determining impacts on air quality for example allows the understanding of how this will affect the surrounding area, such as residential areas and the quality of life. This is determined through air modelling within a GIS. Fig. 5.4 demonstrates the environmental mitigation cost for the analysis of determining the best roads construction alternative.

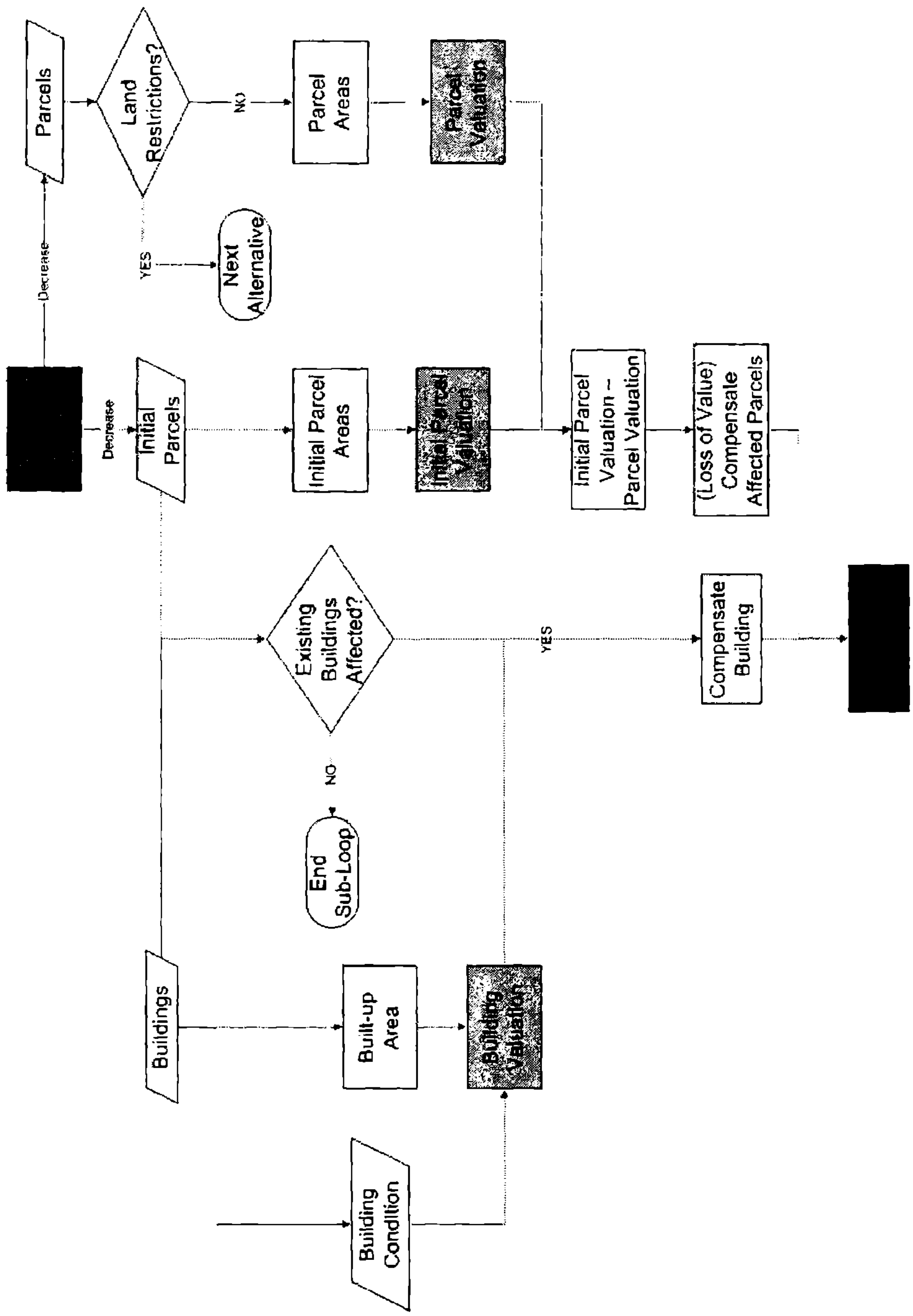

Figure 5.3 FLOW FOR LOSS VALUATION OF PARCELS AND COMPENSATIONS

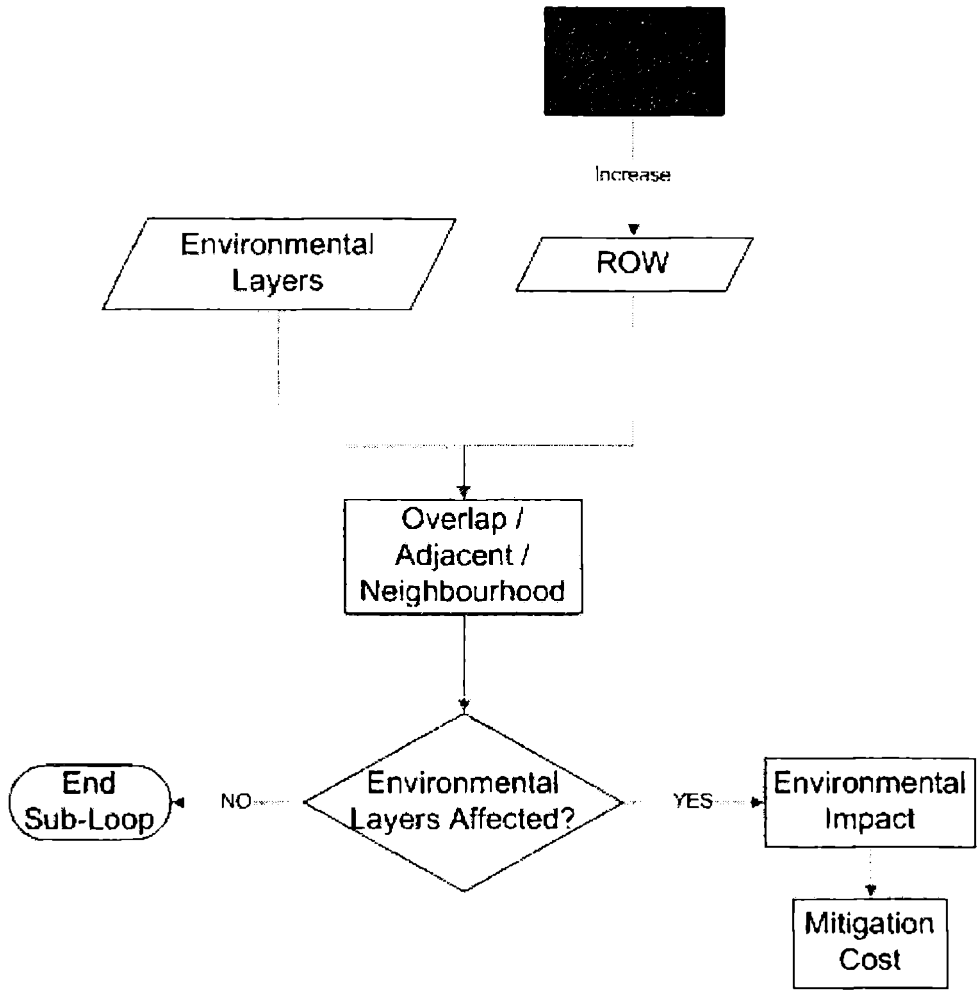

Figure 5.4 MITIGATION COST DUE TO ENVIRONMENTAL IMPACT

5.2.4 Environmental Impacts

Roads degrade agricultural production and environmental factors directly through paving and clearing lands. It also degrades them through encouraging increased development through land use, urban sprawling, and fragmenting local species of wildlife. Air pollution is increased through roads. Also, paved surfaces increase temperatures which can affect the ecological system of the area.

Banzhaf and Jawahar (2005) identify the following benefits from preserving undeveloped lands within urban outskirts:

a. Protecting groundwater
b. Protecting wildlife habitat
c. Preserving natural places
d. Providing local food
e. Keeping farming as a way of life to increase agriculture and preserving food resources
f. Preserving rural character
g. Preserving scenic quality
h. Slowing development
i. Providing public access

Roads cause the following environmental impacts which need to be addressed for mitigation.

a. Road kills: Animals killed directly by motorists. Road kills increase with traffic speeds and volumes.
b. Species fragmentation and isolation: Roads can form a barrier for species movement and therefore can prevent the interaction of wildlife and therefore affects breeding directly. This reduces population health and genetic viability.
c. Exotic species introduction: Some plants thrive in disturbed habitats alongside roads and can spread into native habitat competing with native species.
d. Pollution: Roads cause air, noise, and water pollution.

e. Impacts on terrestrial habitats: habitat disruption and loss.
f. Impacts on hydrology and aquatic habitats: Road construction affects water quality, quality, channels, and groundwater quality.
g. Human interaction: Roads bring public access to the native ecological habitat by introducing irresponsible visitors and hunters.
h. Sprawl: Roads act as a catalyst for development, which stimulates demand for utility services and public facilities, which stimulate urban development even further.

Roads also degrade the health of landscape and cultural heritage, which are important to attract tourism and parcel valuation (Fausold and Lileiholm 1996). Roads construction also has a mixture of both positive and negative social impacts, depending on traffic volume and connectivity of communities. It can increase social interaction by allowing accessibility. However, at higher traffic volumes within urban areas which are vehicle oriented may tend to reduce social interactions.

Transport decisions affect land use patterns. Vehicles need large amounts of land for roads and parking facilities. They also encourage lower-density sprawling. These land use changes impose various economic, social, and environmental costs.

6. GIS Traffic Flow Analysis for Road Alternative Evaluations

6.1 Introduction

Just as the bloodstream ensures the transport of nutrients, oxygen, and waste between organs, so is the road network ensures the transport of goods and services within a geographical area. The main reason for building roads is to allow this traffic. Therefore, this is one of the most important parts for determining the best roads construction alternative. Over-designing a road network is bad management, because public funds are wasted. Similarly, under-designing a road network restricts the growth of an urban or rural area and thus adversely affects the economy.

Inasmuch, traffic analysis is divided into two main categories, i) traffic flow, and ii) traffic safety. In this research, each of those categories are look at individually. In general, the factors that are best for traffic flow are not always the best for traffic safety and vice-versa. However, traffic safety and traffic flow does not necessarily mean that they do not move hand-in-hand. On the contrary, the less accidents on a road, the better is the traffic flow. Hence, what is best for traffic safety is best for traffic flow, but what is best for traffic flow does not necessarily mean it is best for traffic safety.

What this really means is simple. The road capacity is always determined by the number of vehicles a road can service within a period

of time. It is, therefore, natural to say that the faster the vehicles, the more vehicles will pass through a road and thence, the higher capacity the road has. All factors that reduce road capacity are evidently the same factors that would reduce speeds of vehicles. However, roads would not be designed for unreasonably high speeds due to the adverse safety effects.

There are many traffic simulators that simulate traffic flow. There are very few that simulate traffic safety. It is necessary to increase research in simulators that have the capability to simulate both flow and safety to understand how the flow is affected by traffic incidents based on the frequency of expected number of different types of incidents.

When comparing different roads construction designs, it is equally important to evaluate the effects of incident management. For example, if all indicators show that two alternatives are almost exactly the same, there still may be a difference on how well incidents are managed in each. Therefore, the scale of comparison may be drifted based on the performance of the design during incident management. Hence, different scenarios need to be developed to get a more accurate performance indicator for the overall traffic.

In traffic flow, the performance indicators that need to be input to the GIS model for comparison includes the following for both macro-level and micro-level evaluations:

Table 6.1 Traffic Parameters

1	Level of Service (LOS)	Measuring operational conditions within a traffic stream based on service measures, including speed, freedom to manoeuvre, traffic interruptions, etc.
2	Speed	Rate of distance per unit of time
3	Volume	Number of vehicles passing a road segment in a specific time interval
4	Travel Time	Average time for vehicles traversing a facility, including control delay.
5	Travel Distance	Space distance between origin and destination.
6	Ridership	Occupancy of passengers on the transit system
7	Average Vehicle Occupancy (AVO)	Average occupancy per vehicle including public transportation, such as buses
8	Volume to Capacity Ratio (v/c)	Ratio of flow rate to capacity
9	Density	Average number of vehicles within a space segment of road facility
10	Vehicle-Miles of Travel (VMT) / Person-Miles of Travel (PMT)	Total distance travelled by all vehicles in a road segment during a specified time period
11	Vehicle-Hours of Travel (VHT) / Person-Hours of Travel (PMT)	Total travel time spent by all vehicles in a road segment during a specified time period
12	Delay	Additional travel time spent by travellers during lower than free flow speeds, signal operations, and turn penalties
13	Queue Length	Length of queue waiting to be served due to reaching travel demand over capacity of road (or during incidents).
14	Stop Penalties	Number of stops experienced by a road segment, including signal phasing.
15	Crashes	Average number of crashes expected in a segment of road
16	Incident Duration	Average duration of incidents, including crashes, vehicle failure due to mechanical or tire problems.
17	Travel Time Reliability	Expected probability of reaching higher travel demand due to incidents, weather conditions, special events.
18	Emissions Fuel Consumption	Predicted emissions for each pollutant type in a network depending on average emissions of vehicles using roads (broken down to percentage of types of vehicles)
19	Noise	Sound levels produced by traffic
20	Mode Split	Percentage of travellers using each travel mode.
21	Benefit / Cost Ratio	Quantifying the ratio of monetary benefits to total costs of traffic improvements and maintenance.

The total time spent (b) is the sum of the total travel time and the total waiting time. The vehicle loss time (a) is defined by the difference between the total time spent and the time spent in case all vehicles were travelling at freeflow or at prevailing speed limits.

The average travel time is defined by the total time spent over the total number of vehicles that experience this travel time. The average travel time determines the average vehicle speed (g). The mean link speed (f) is the arithmetic mean speed for all links in the network within a specified period of time, usually testing is done for peak hour.

The mean queue length (e) is defined according to the time-average length of the queue. The total distance travelled (h) is the sum of all instantaneous travel distances during the time of the test, usually peak hour.

The total inflow (i) and outflow (j) of the network are defined by the sum of all inflows and outflows respectively. The number of vehicles in the network (l) is defined by the time-average number of vehicles present during the testing period (i.e. peak hour). This is determined as the product of the average density on a link and the length of the link. The number of vehicles in queues (m) is defined by the time-average number of vehicles at the queues during the testing period (i.e. peak hour). The total number of vehicles (k) is the sum of the number of vehicles travelling in the network (l) and the number of vehicles waiting in the queue (m).

An estimate is evaluated for the total consumption of fuel (n). This of course can be calibrated to match actual average fuel consumption by all the vehicles in the network. This depends on the different types of vehicles and fuel used, which will be variable in different geographical areas. However, it is assumed that types of vehicles will be similar to the different roads construction alternative evaluated.

6.2 Performance of Traffic Flow Operations

To understand how to decide between different roads construction alternatives, one needs to understand what the current conditions are and what is expected by each proposed alternative. Traffic authorities need to realize the strategies for the best alternative and understanding the necessary allocation of funds.

Three main traffic variables determine traffic flow in a macroscopic level i) flow (the number of vehicles counted in unit time), ii) occupancy rate (assessment of concentration of traffic), and iii) speed (distance travelled in a unit of time).

A performance indicator is the aggregation of variables that are both spatial and temporal. When comparing the performance of different road design alternatives, it is important to look at the effects from a macroscopic point of view on a network-level and a microscopic, from a project-level.

The total length of a trip is defined as the sum of all lengths of each road section, l_i, with a traffic flow, q_i, and speed, v_i. Thence, the total length is given by

$$L = \sum_{i=1}^{n} l_i \ . \qquad \text{(Eq. 6.1)}$$

The total vehicle distance travelled by all vehicles within a comparative period is given by

$$D = \sum_{i=1}^{n} q_i l_i \ . \qquad \text{(Eq. 6.2)}$$

Based on the above equations, the average flow is expressed by

$$Q = \frac{D}{L} . \qquad \text{(Eq. 6.3)}$$

The total time spent by all vehicles during the time period for making the trip is given by

$$T = \sum_{i=1}^{n} \frac{q_i \cdot l_i}{v_i} \ . \qquad \text{(Eq. 6.4)}$$

The average speed is defined as the distance travelled over the time spent. It is a harmonic mean, which is weighted by both the length of the

road section and the flow. The length is a static factor, while the flow is dynamic. The average speed is therefore given by

$$V = \frac{D}{T}. \qquad \textit{(Eq. 6.5)}$$

The average trip travel time is given by

$$TT = \frac{L}{V}. \qquad \textit{(Eq. 6.6)}$$

The average trip travel time of a group is the mean trip time of individual vehicles on all sections of the road. Journey times displayed in Vehicle Mean Space (VMS) diagrams are obtained from speed value, which is one of the macroscopic traffic parameters. The problem, however, it is not possible to evaluate individual trip time from macroscopic variables. The parameters from a macroscopic level are evaluated based on the overall performance of the links. Thus, from a macroscopic level, the average trip travel time is evaluated from statistical data and by following space-time diagrams, such that delays may be included. Therefore, the expression is in the following form:

$$ATT = \frac{L \cdot \sum_{i=1}^{n} \left(\frac{q_i(h_i) l_i}{v_i(h_i)} \right)}{\sum_{i=1}^{n} \left(q_i(h_i) l_i \right)}, \qquad \textit{(Eq. 6.7)}$$

Where

h_i = the time of arrival on the road section for a vehicle leaving VMS at time t.

$q_i(h_i)$ = the flow on the road section at time h_i.

$v_i(h_i)$ = the speed measured at the same instant.

The total delay, which is expressed in units of time, is defined as the difference between the time spent at actual speeds, v_i, and that evaluated using design speeds (or speed limits), v_i^r. The total delay, R, is given by

$$R = \begin{cases} \sum_{i=1}^{n} \left[q_i \cdot l_i \cdot \left(\frac{1}{v_i} - \frac{1}{v_i^r} \right) \right], & v_i < v_i^r \\ 0, & v_i \geq v_i^r \end{cases} . \qquad \text{(Eq. 6.8)}$$

Fluidity is a scale that measures the ratio of the time spent at design speeds (or speed limits) with the time spent at actual speeds. It is given by

$$F = \begin{cases} \dfrac{\sum_{i=1}^{n} \frac{q_i \cdot l_i}{v_i^r}}{\sum_{i=1}^{n} \frac{q_i \cdot l_i}{v_i}}, & v_i < v_i^r \\ 1, & v_i \geq v_i^r \end{cases} . \qquad \text{(Eq. 6.9)}$$

The fluidity scale is, therefore, already bounded between 0 and 1, which is an ideal ratio for a performance indicator for reasons of avoiding bias.

Congestion can be measured as a reciprocal of the fluidity scale. When looking from a network-level, the density of congestion is evaluated as the average of the whole network, where road sections are operating below critical speed, v_c. If there is no congestion, in other words, when the actual speeds are not below critical speed for each section, then the indicator is unity. The contribution of each section depends on the flow measured on it. The density congestion is therefore given by

$$C = \frac{\sum_{i=1}^{n_1} \frac{q_i \cdot l_i}{v_i} + \sum_{i=1}^{n_1} \frac{q_j \cdot l_j}{v_c}}{\sum_{i=1}^{n} \frac{q_k \cdot l_k}{v_c}}. \qquad \textit{(Eq. 6.10)}$$

The density congestion, C, does not theoretically have an upper limit due to the fact that $\sum_{i=1}^{n_1} \frac{q_i \cdot l_i}{v_i}$ does not have one.

Other indicators of traffic flow operations are capacity and level of service, although it is not limited to them. The capacity of a road or an intersection determines the degree of saturation and is evaluated as a ratio of the demand flow rate (volume) to the capacity (v/c ratio). On the other hand, the level of service is evaluated based on the average stopped delay per vehicle. Traffic flow models penalize based on the number of average stops. It also penalize based upon the number of

turns and the added delay due to slowing down of vehicles due to turns or even due to certain traffic controls, such as yield signs.

In literature, many researchers have used the grey system theory and put it in use with many applications, including grey relational analysis, grey prediction and forecasting, grey clustering, as well as decision making and grey control. Examples of such applications are found in Cai (1993), Chang et al. (1999), Chang (2000), Huang (1996), and Wong (1999). The grey system theory is multidisciplinary or genetic theory. Grey system theory has similarities with fuzzy logic as it is an effective mathematical means for solving problems that contain uncertainties and indeterminate parameters.

Many factors govern the operations of road segments and intersections, including motor vehicles, bicycles, pedestrians, signal control, geometric design, and environmental conditions. The following assumptions should be valid for unbiased selection criteria:

a. The indices should be able to comprehensively indicate the operational qualities of mixed traffic, and they must have clear concepts.
b. The parameters that are associated with the indices should be as simple and practical as possible.
c. Indices that are incomparable and interrelated should not be used.
d. Field survey data that are relevant to the indices should be collected in a convenient manner.

The degree of saturation is one of the essential parameters that indicate the operational performance of an intersection, and it is defined as the volume to capacity ratio (v/c). However, this parameter must be looked at per lane group. For example, it is possible to have an intersection with an excellent v/c ratio, whereas a lane group is disadvantaged with considerable delays. This might occur when combinations of the following conditions coexist:

a. The cycle length is too long
b. The lane group is disadvantaged by the signal timing having a long red time
c. The signal progression for the main traffic is poorly coordinated.

Thence, the v/c ratio is not sufficient to determine the performance and quality of service of a road section or intersection. Hence, the average stopped delay (SD) is used and is considered to be the most relevant parameter to the level of service of signalized intersections, whereas the v/c ratio is best used for freeway sections.

The main reason for evaluating stopped delay is to compute the amount of loss of travel time and fuel consumption. Hence, when looking at those two parameters, the method of evaluation is therefore sought. The stopped delay (SD) is also a measure of frustration and discomfort of motorists. The delay can be measured from field counts and computed as follows:

$$SD = \frac{\textbf{sum of stopped vehicle count} \times \textbf{interval between stopped vehicle counts}}{\textbf{total volume that is observed during the study period}}$$

(Eq. 6.11)

The stopped delay (SD) is measured in seconds and is a good evaluator of the level of service of each lane group in an intersection. However, this may not always be the best evaluator for freeway sections since in high congestions, it is not always true that vehicle must be stopping and queuing, as this would usually only be the case for LOS E or F.

In addition to the above two indices, the queue length (QL) is also another parameter that is necessary. QL is defined as the distance from the stop line to the last vehicle that joins the queue during one red interval. This parameter, however, is only true for signalized intersections. If the QL is longer than the road section, then the overflowing queue could block operations in upstream intersections. Therefore, the average queue length (QL) must be used in conjunction with v/c ratio and average stopped delay.

The above three parameters alone are not the only parameters to consider for traffic flow. It is also as important to consider the conflict. This is not to be confused with safety performance by understanding methods of reducing conflict points due to safety measures. In mixed traffic conditions, motor vehicles encounter conflicts with pedestrians, bicycles, and others that would disrupt that flow of motor vehicles within an intersection.

6.3 Evaluation of Performance of Traffic Flow Operations (Micro-level)

Deng (1985) has defined a grey number, $\otimes x$, as an interval that has known upper and lower bounds, but does not have the actual distribution of each individual index *x*:

$$\otimes x \in \left[\underline{\otimes} x, \overline{\otimes} x\right],$$

Where $\underline{\otimes} x$ is the lower bound and $\overline{\otimes} x$ is the upper bound.

The evaluation carries multidimensional parameters. Each of the values v/c, SD, and QL are not in the same scale. Therefore, it is necessary to normalize the values and have them re-scaled, such that they can be comparable with each other.

For each performance indicator *x*, for v/c, SD, and QL, and upper bound and lower bound values are given. Consider the following:

$x_1 = v/c$

$x_2 = SD$

$x_3 = QL$

Accordingly, the Performance Indicator for traffic flow (PI_{tf}) is defined as follows:

$$PI_{tf} = \frac{\sum_{i=1}^{n}(w_i \times x_i)}{n}, \qquad \textit{(Eq. 6.12)}$$

Where,

w_i = weight given for each parameter.

w_i is a weighting that is a percentage of importance given for each parameter from the overall score (*s*), and therefore is by definition described as follows:

$$w_i = \frac{s_i}{\sum s_i}. \qquad \textit{(Eq. 6.13)}$$

When comparing the v/c ratio for different alternatives, it is necessary to identify the value for each lane group within the same alternative and then an average is computed to compare between different designs (or signal phasing). When computing the average v/c ratio, it is necessary to do a weighted average to remove any bias as follows:

$$x_1 = \frac{\sum_{i}^{n}\left[w_i \times \left(\frac{v}{c}\right)_i\right]}{n}. \qquad \textit{(Eq. 6.14)}$$

Similarly, average stopped delay needs to be determined as a weighted average for each lane group (i.e. approach).

$$x_2 = \frac{\sum_i^n [w_i \times (SD)_i]}{n}. \qquad \textit{(Eq. 6.15)}$$

Likewise, average queue length needs to be determined as a weighted average for each lane group (i.e. approach) as well.

$$x_3 = \frac{\sum_i^n [w_i \times (QL)_i]}{n}. \qquad \textit{(Eq. 6.16)}$$

All parameters need to be evaluated for their maximum values during peak hour.

Other performance indicators are as important. Level of Service (LOS) is a common indicator. However having a v/c ratio, which is a parameter used to determine the LOS, would suffice. In principal, it would not matter much which is used in the model. Delay is used, which is substituted as fluidity (F) in this research as discussed earlier. Although spillback (SB) and queue length (QL) are related, it is still important to evaluate spillback independently, as it would be part of the queue length that would obstruct other traffic in the network. Fuel consumption (FC) and fuel emissions (FE) are common indicators. Although this predominantly relies on the type of vehicles used in different links on a network, they are not meant to be used to compare different links on a network that would be utilized by statistically significant different types of vehicles. However, when comparing different roads design alternatives,

it is assumed that same travelers are traveling the road regardless of the design alternative used.

With such a glance, it can be concluded that the following performance indicators are necessary to include for comparative evaluation purposes:

1. Fluidity (F)
2. Volume-Capacity ratio (v/c)
3. Stop Delay (SD)
4. Queue Length (QL)
5. Spillback (SB)
6. Fuel Consumption (FC)
7. Fuel Emissions (FE)

In the micro-level, it is therefore important to have a weighted performance indicator that follows the following suit:

$$PI_{tr(micro)} = w_F \cdot F + w_{v/c} \cdot \left(\frac{v}{c}\right) + w_{SD} \cdot (SD) + w_{QL} \cdot (QL) + w_{SB} \cdot (SB) + w_{FC} \cdot (FC) + w_{FE} \cdot (FE)$$

(Eq. 6.17)

Each factor, such as fluidity, stop delay, and others are not easily comparable with each other since their values have different values from each other. Thence, the weighting is defined as follows:

$$w = \frac{s}{[MAX(x)]_i \cdot \sum s_i},$$

(Eq. 6.18)

Where

s	=	weighting score
$MAX(x)$	=	the maximum factor of the indicator for any of the

alternatives.

Thence, each parameter within the performance indicator, $PI_{tr(micro)}$, becomes dimensionless (without units) and therefore, mathematically comparable.

6.4 Evaluation of Traffic Network Flow (Macro-level)

When evaluating different road design alternatives, its impact on the network flow is critical. This is compared to the impact on the maritime network flow when the Suez or Panama Canals were built. It is possible that minor improvement on a certain location on the road network can have a significant impact on the full network, such as treating bottlenecks might be a minor road widening on a certain location on the road, whereas the impact on the network is great.

Mackie and Nellthorp (2001) developed a generalized cost formula in a cost-benefit analysis, which includes time, user charges (i.e. tolls), and vehicle operation cost, as cost per distance. The unit traffic costs are evaluated as the sum of travel time and vehicle operation costs. The road user cost is effective in evaluating how much a new design can save compared to the current situation.

$$(TC)_i = C_{tt} + C_{vo} = \frac{l_i}{v_i} \times \alpha \times l_i \times \gamma, \qquad \textit{(Eq. 6.19)}$$

Where,

$(TC)_i$	=	traffic cost
l_i	=	distance between nodes of interest in the network
v_i	=	traffic speed on a link
α	=	unit cost for travel time in unit of currency per hour
γ	=	unit cost for vehicle operation in unit of currency per unit of distance

The link-capacity function, as described by Papacostas and Prevedouros (2001), define a relationship between v_i and the total traffic flow on the link. The link-capacity function in accordance to the Highway Capacity Manual (HCM) is developed as follows (Martin and McGuskin 1998):

$$v_i = \frac{v_i^0}{\left[1 + 0.15 \times \left(\frac{F_i}{F_i^C}\right)\right]} \qquad \textit{(Eq. 6.20)}$$

Where,

v_i^0	=	free-flow traffic speed on the link
F_i^C	=	link traffic flow capacity

v_i^0 may be deterministic, based on the functional classification of the link, whereas F_i and F_i^C are random variables.

The unit cost for travel time, α, is valued based on trip purposes of business, personal, and good transport (Oort 1969; Steenbrink 1974). It is assumed, however, that similar purposes of trips and users are using the road network, regardless of which alternative is chosen. Therefore, this variable would not affect the result of alternatives evaluation. Although vehicle operation costs depend on the type of vehicle, it will not be assumed as such in this study, since the same type of vehicles are presumed to use the road. Similarly, the unit cost for vehicle operation, γ, is also presumed consistent.

The Level of Service (LOS) is a function of the free-flow speed, which is defined by the Highway Capacity Manual (HCM) as follows (TRB 2000):

$$F_i^C = v_p \times PHF \times N \times f_{HV} \times f_p \,. \qquad \textit{(Eq. 6.21)}$$

v_p	=	maximum service flow rate associated with the free-flow speed and LOS
PHF	=	peak hour factor
N	=	number of lanes
f_{HV}	=	heavy vehicle factor
f_p	=	population adjustment factor

Traffic volume is one of the most important inputs to the model. Traffic volume may be obtained as the predicted Average Daily Traffic (ADT) of the link, and can be based on simulations. According to HCM 2000 (TRB 2000), the relationship between ADT and F_i is expressed as follows:

$$F_i = K \times D \times ADT\,, \qquad \textit{(Eq. 6.22)}$$

Where,

K	=	K-factor
D	=	Directional-factor

By such, ADT is converted to the average hourly traffic flow in one direction.

In conclusion, from a macro-level point of view, the performance indicator is the sum of the traffic cost on entire links for a trip:

$$PI_{tr(macro)} = \sum (TC)_i \qquad \textit{(Eq. 6.23)}$$

6.5 Evaluation of Road Structures Reliability

Reliability of road structures is very important to understand the life span of a road network. This is extremely important to understand the amortization of the cost of construction and maintenance. Since the reliability of structures is also based on physical conditions, it is assumed that when evaluating different alternatives, a physical condition is non-existent.

Besides the physical conditions of a structure, the reliability of road structures is based on its location, mainly for climate parameters and traffic conditions. However, that as well, is not a major criterion when

evaluating different alternatives. The reason is that it is expected that all alternatives will carry similar traffic conditions and are located in the same, or at least, in the same proximity as one another.

Consequently, the evaluation of road structures reliability is done based on the cost of construction and maintenance, which is discussed in Chapter 8.

6.6 Evaluation of Other Traffic Parameters

Arguably in some literature, it is important to evaluate user satisfaction to understand the best road alternative. However, the user satisfaction is defined by Augusti et. al. (1998) as the probability that a network can meet a specific level of traffic flows among any nodes of interest in the network. However, it is found that this criterion is redundant, because the input data from the model to evaluate this criterion is already used for the evaluation of traffic flow parameters.

In general, as the traffic flow reaches and exceeds the capacity, the satisfaction level is deteriorated. However, this is also true as the Level of Service (LOS) also decreases. Other intangible user satisfaction parameters, such as comfort and convenience levels are also usually in direct proportion with the parameters that affect the Level of Service (LOS).

6.7 Building a Traffic Flow Model for Supply and Demand

There are many types of data that address traffic flow. Perhaps the most fundamental is the street network, since this forms the spatial framework

for various attributes, including speed (kph), volume (vph), directional splits (left, right lanes), multiple lanes (including turn bays), occupancy (% of time there is a vehicle occupying a location), vehicle type (generally, number of axles), level of service (LOS) (an *A* to *F* subjective rating of congestion, where A is freeflow and F is standing traffic), time (date, time, day of week), and *metadata* that can be used to characterize and manage the data (sampling interval, analysis methods used, error, etc.)

The traffic model needs to comprise the supply and demand. The travel demand is in direct relations with the planning model, as discussed earlier. Once the supply and demand have been assessed, traffic flow can be evaluated. According to Cervero and Hansen (2000), supply and demand can be summarized by the following estimated two-way system of equations,

$$D_{it} = f\,(S, P, A, I, L, F)_{it} \qquad \textit{(Eq. 6.24)}$$

$$S_{it} = g\,(D, A, L, G, F)_{it} \qquad \textit{(Eq. 6.25)}$$

Where,

D = Travel demand vector (e.g. vehicle miles traveled)

S = Roadway supply vector (e.g. lane miles of major road facilities)

P = Price vector (e.g. fuel price per gallon)

A = Population Attribute vector (e.g. population size; demographics)

I = Income-effects vector (e.g. per capita income levels)

L = Localized-effects vector (e.g. land-use densities; meteorological characteristics)

G = Governance and policy factors vector (e.g. state political party

affiliations; air quality levels)

F = Fixed-effects vector (e.g. country-specific dummy variables to account for unique and idiosyncratic characteristics, such as the effects of an earthquake on travel demand and road building in any particular county at any time point)

i = Cross-section observation

t = Year time point

Since it takes time to propose, evaluate, design, program, and build new supply for the road capacity, a lag time is necessary when investigating the current traffic volumes and future forecast. When feasibility studies are to be made, the current status of the traffic flow needs to include future forecasts of the traffic volume from the time of proposal to the time of completion of the construction. This may take from few months to years, depending on the estimated length of time to complete such a project.

Therefore, the model starts with supply-demand analysis. Each road construction alternative will go through the test of supply and demand of the road network. It would, naturally, take into account the available transportation alternatives as a factor. In other words, the demand for the road network is a percentage of the overall demand for a transportation system. A separate analysis of how much of the demand will be for the road network is made, especially in multi-modal systems where water ferries and rails are used.

Important to note that it is not necessary if a road design is inadequate for the demand on the network that it should not be considered, as other

roads might have already been planned to absorb more of the demand. Therefore, this analysis is to compare the amount of demand that is being serviced by different alternatives as part of the cost versus benefit analysis. The amount of demand that is serviced by each alternative is, consequently, the benefit imparted in this analysis.

6.8 Delay Times

Traffic delays and queues are principal performance measures that are used to determine level of service (LOS). A descriptive model of traffic flow is used in the research for a better understanding of the interaction between demand and supply of the traffic network. Traffic flow comprises of two components, which include deterministic and stochastic to reflect both the fluid and random properties of traffic flow.

The deterministic component of traffic is founded on the fluid theory of traffic in which demand and service are treated as continuous variables described by flow rates which differ in the time and space domain. The stochastic component of delay is based on steady-state queuing theory that defines the traffic arrival and service time distributions.

Traffic safety is an important issue in urban transportation networks. However, safety and traffic flow delay are not usually the best of acquaintances. However, with the advancement in computer traffic simulations and models, many techniques have been revised to achieve a harmonious solution to optimize both safety and traffic flow.

One of the biggest major traffic conflicts in intersections is the left-turn. Conflicts of left-turn movements cause many crashes, and their severity are also higher, since most crashes approach at a 90^{0} angle. Thence, this chapter will look into two methods to alleviate this conflict problem. Alternative network and intersection geometry designs will be looked at that may alleviate the left-turn movement conflict problem. This attempts to enhance the traffic safety performance of a road design.

To reduce left-turn conflicts in a network, there are the following alternatives:

1. Alternative Network Design:
   a. Make the network One-Way only, this will allow left-turns to be treated similar to right-turns
   b. Completely eliminate left-turns in the network

2. Alternative Geometry Design:
   a. Restrict Left-Turn movements to protected left-turn only
   b. Introduce grade-separated left-turns in the network
   c. Continuous Flow Intersection (CFI)

6.9 Example of Comparison between Alternative Network Designs

There are many advantages to change the network design, as it may manage problems in a wider area. However, this can be compared as a holistic treatment of a disease. Though the disease is being treated by accommodating different factors, it may miss some of the specific

problems caused by the disease, or caused by the holistic treatment method.

For example, if traffic problem is compared with blood circulation in the human body, it will be found that congestion in the blood flow to the head may cause headaches. There are several methods to treat this problem, two of which are as follows, i) taking pain relievers to ease the pain; or ii) taking medication that regulates the constriction of blood vessels in general to stop the occurrence of the headache.

Similarly, traffic congestion causes headaches. There are many different treatments to this problem, two of which are as follows, i) changing the geometry of the intersection so that you regulate the conflicts and delays without necessarily adding more capacity to the network; or ii) increasing the intersection capacity to accommodate for more traffic.

Changing the design of the network instead of the geometry may have many cost-effective advantages. Since the geometry is not changing, no additional right-of-way is required and therefore land acquisition may be avoided cutting costs. Also, it does not have any extensive planning impacts that geometry designs sustain within the direct vicinity of the road.

This section delves into the advantages and disadvantages of changing the network design, looking at the two methods of changing the network design, i) changing the network to one-way only; or ii) eliminating left-turns in the network.

6.9.1 Changing the Network to One-Way Only

Sometimes, it is convenient to change the network design instead of the geometry. It is less of a financial burden as it may be very cost-effective in alleviating traffic conflicts. When changing a network from dual-carriageway to single-carriageway, there could be significant planning advantages. If there were a median on the road, and since a median would no longer be required, the median can be converted to an additional lane. Thus, an increase in the traffic capacity is also achieved immediately. If it is decided that additional capacity is not required, the road would be narrowed, instead of widened, by eliminating the median. Most researchers cannot imagine that narrowing the road network can actually achieve better traffic performance. However, it is possible by converting two-way traffic to a one-way, when eliminating the median. In this method, a two-street is converted to a one-way street, helping the traffic flow within the network.

In a planning perspective, it is not only advantageous to have an additional right-of-way (ROW), but also there are other benefits when the right-of-way is narrowed to allow for more land to be utilized. Hence, when assessing land valuation with respect to planning, it is important to optimize between land use and the right-of-way.

6.9.1.1 Advantages of One Way Network

A One-Way only network is very helpful in optimizing traffic flow. Also, since one-way streets may not require as a big capacity as two-way streets, the number of lanes in an intersection is therefore reduced, allowing for a better pedestrian crossings. In light of this study, left-turns

in a one-way network, though still existing, are not treated any differently than right-turns, as the conflict type is reduced to only a merging point, instead of a 90° conflict. Therefore, such a network will reduce left-turn delays, and therefore decreasing the travel time through the area.

Advantages of one-way networks include:

1. Increased capacity
2. Increased traffic flow speeds
3. Increased traffic flow through Traffic signal coordination
4. Reduced certain intersection accidents (left-turn accidents)
5. Reduced pedestrian crossing delays
6. Reduced lane width, as no buffer between opposing lanes are required, or the additional width can be used for street-parking

6.9.1.2 Disadvantages of One Way Network

Perfection is a vision that people attempt to reach, but practically are hindered by reality. There are several disadvantages that permeate in one-way networks. Business and commercial districts may be disadvantaged by a one-way traffic flow model as it restricts access and circulation. Drivers would have to navigate longer and possibly cumbersome routes along one-way streets to reach their destinations.

Disadvantages of one-way networks include:

1. Longer trip distances
2. Higher fuel consumption
3. Higher turns rate, which may affect the street volume capacity
4. Higher lane change and mid-block accidents

5. Left-turn queuing in traffic light phasing

6.9.2 Eliminating Left-Turns in a Network

When a cancerous tumour cannot be treated through medications, its surgical removal will be deemed necessary. Similarly, if left-turn conflict problems cannot be treated through other means, its elimination from the network may be necessary. However, there are advantages and disadvantages in such networks.

Prohibition of left-turns can be made only if other convenient alternatives are available. This may include a series of right-turn movements around the block that will permit the arrival to the desired destination.

Using network analysis within TransCAD® three points have been chosen, a starting point 1, a first stop 2, and a final destination 3. By finding the shortest path without any left-turns allowed, the result can be seen in Figures 6.1 and 6.2.

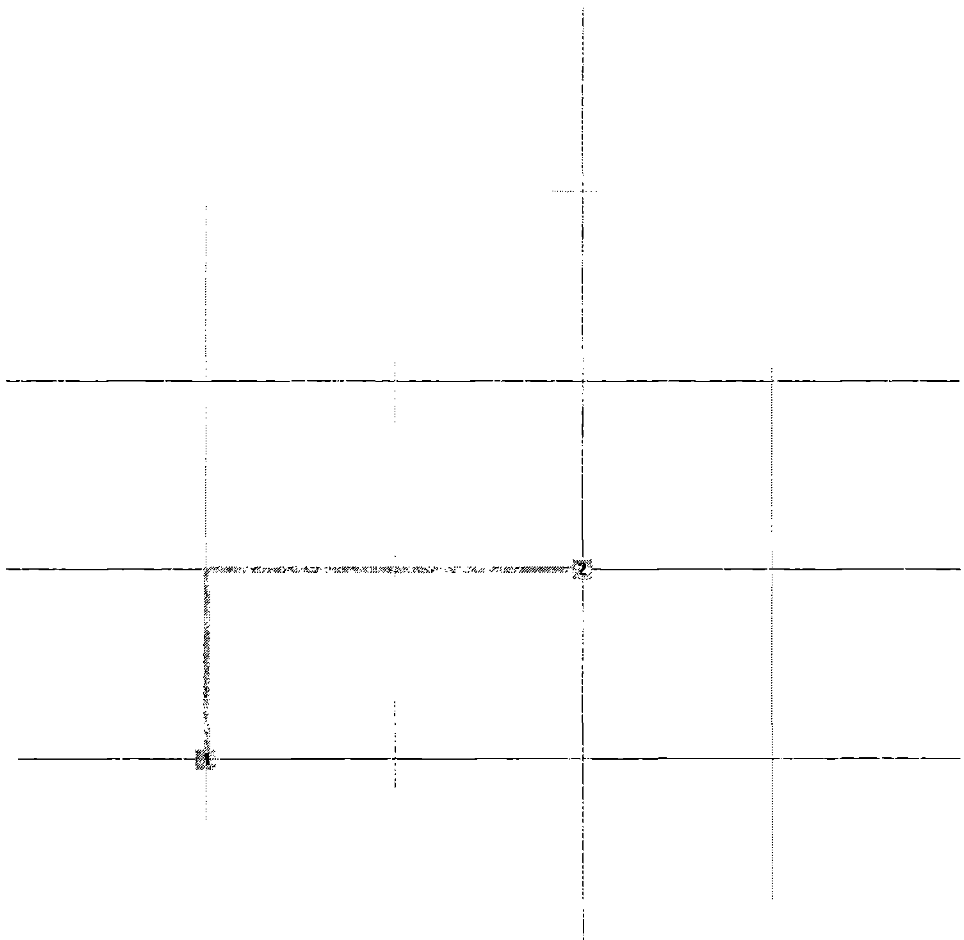

Figure 6.1 FIRST STOP AT POINT 2

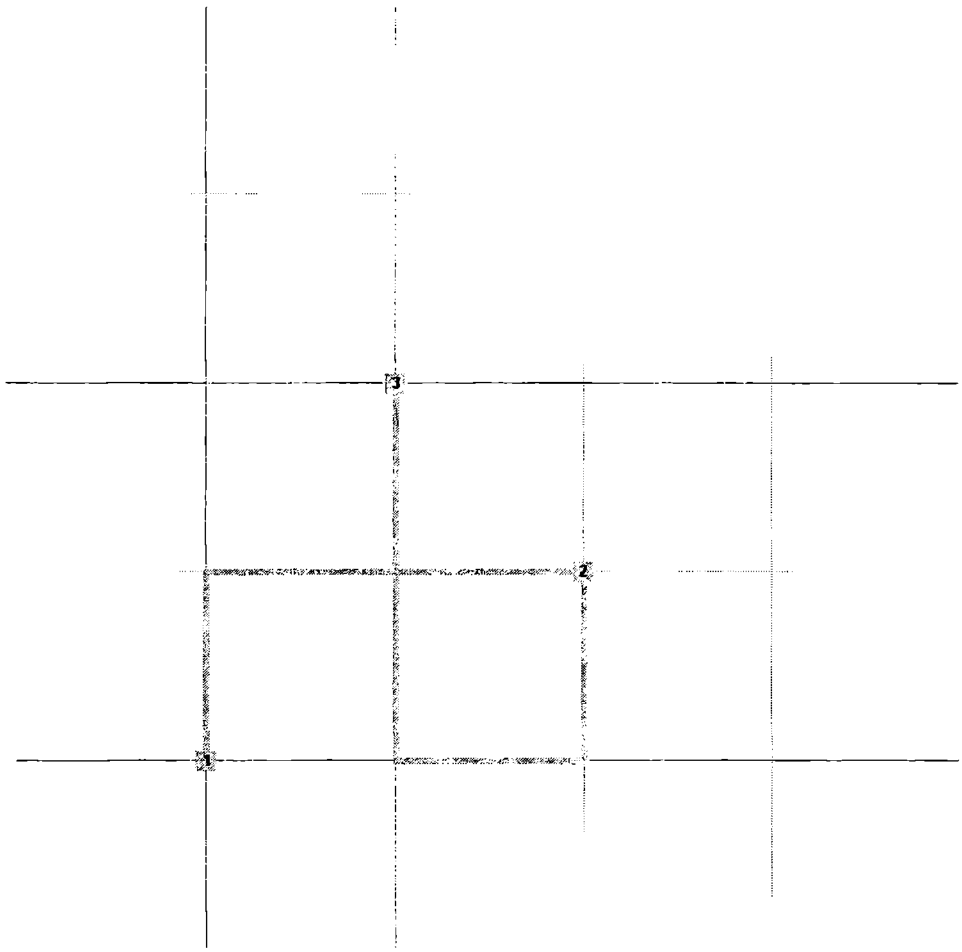

Figure 6.2 FINAL DESTINATION AT 3 WITHOUT LEFT-TURNS

From the analytical results, it can be seen that travelling from points 2 to 3 would have traditionally been possible through a double left-turn travelling on two segments of the road. However, since a penalty was imposed on left-turns, an alternative path has been shown with only right-turns, but travelling on four segments of the road. Therefore, the path has increased by two segments to make up for the elimination of the left-turn. Nevertheless, the increase on the length of the path that needs to be taken by avoiding left-turns is not always fixed. As shown in

Figure 6.3, travelling from points 2 to 3 would have been through one left-turn and travelling on one segment of the road only. However, since left-turns have been eliminated, the travelling distance has increased by an additional four segments of the road using right-turns only.

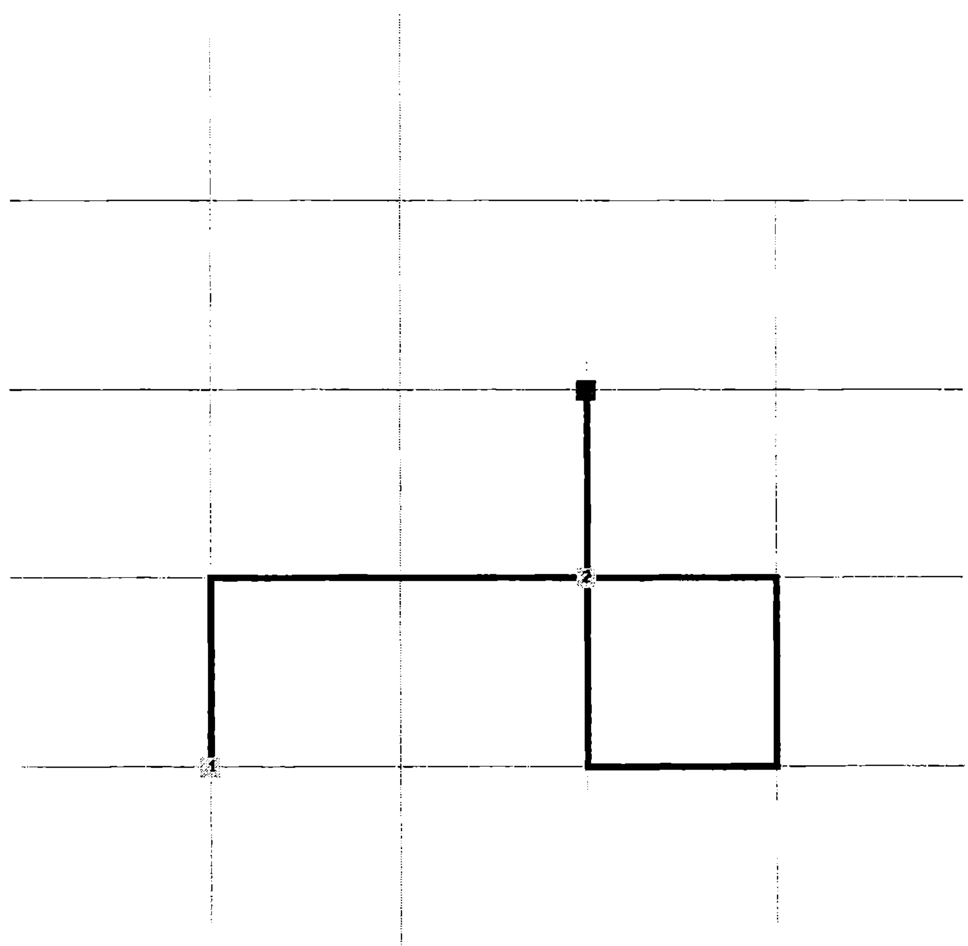

Figure 6.3 NO LEFT-TURNS ALLOWED

Thence, in the given symmetric network where the length of each segment is the same, the lowest bound of how much more would it differ to travel the shortest path between two points by eliminating left-turns

would be zero, as not all trips will require a left-turn anyhow. However, the highest bound would be travelling '*4d*', where '*d*' is the segment length. Therefore, if d is the difference of the length travelled between two points by allowing left-turns and by eliminating them, then '*d*' can be defined by,

$$0 \leq d \leq 4d$$

Therefore, if there were a sequence of multiple point stops (n), then d is defined by,

$$0 \leq d \leq n\,(4d)$$

Conclusively, the more stops required in a trip, the more travel distance will be required, and therefore the more fuel consumption. Hence, the matter of evaluating whether to eliminate left-turns is suitable for a network would be highly determined by the number of multiple stop trips that the network receives, since the performance indicator for traffic flow penalizes on the number of turns and stops. Nevertheless, the additional number of stops may reduce the severity of crashes and therefore advantageous for traffic safety.

Important to note that '*d*' can be reduced on traffic trips with multiple stops through the travelling salesman algorithm. Nevertheless, the difference between allowing left-turns and prohibiting them is bounded as noted above.

6.10 Example of Comparison between Alternative Geometry Designs

Sometimes problems arise locally, and therefore it would not require a complete network change. In traffic flow, for example, a network may be congested. The capacity of the whole network may be increased, but that will create a very high financial burden for construction or the bottleneck that is causing the problem can be redesigned. To reduce left-turn conflicts on intersections, we can attempt to change the design of the geometry of that intersection.

Changing the geometry design of an intersection to reduce the left-turn conflicts may include, 1) restrict intersections to protected left-turn only, which may connote the addition of a left-turn lane; 2) introducing grade-separated left-turns in the network; or 3) using Continuous Flow Intersection (CFI) design.

6.10.1 Restriction of Intersections to Protected Left-turn

A protected left-turn signal phase provides the motorist a period of time where left turns can be made without encountering conflicting vehicular and pedestrian movements. It is usually warranted where the left-turn traffic queue frequently extends beyond the left-turn lane, thus blocking the adjacent through traffic where a significant left-turn volume is present during peak traffic hours or where intersection geometry creates a visibility problem that may be alleviated by introducing a protected left-turn phase. It is also sometimes warranted where approach speeds are high prohibiting motorists to make judgment of gaps.

Motorists typically feel safer when making protected left-turns. Frequency and severity of crashes are also notably reduced. Chapter 7 discusses how signal phasing can directly affect the traffic safety performance of a road design. Unwarranted signal phases create undesirable effects in terms of stops, vehicular delay, and increased fuel consumption.

Restricting intersections with protected left-turns has its advantages and disadvantages in a network, like almost any other decision in life. Protected left-turn greatly reduces the conflicts on intersections. Though the conflict remains, in principle, its consequences are greatly reduced, since the probability of a crash is diminished. One of the parameters that can neither be stated as an advantage or disadvantage is the delay for left-turn drivers. In intersections with high volumes of opposing through traffic, a protected left-turn may reduce the delay time for drivers turning left, as it will give them a higher chance to take the turn. However, in intersections with low volumes of opposing through traffic, the delay time may be increased as left-turn drivers will need to wait longer at the intersection to be able to take the turn.

There are two opposing concepts when glancing at the allowed left-turn movements. Protected left-turns may be warranted for crash reduction or due to intersection capacity. Hence, it needs to be considered not only in traffic flow performance evaluation, but also in traffic safety performance evaluation. Thus, decisions that pertain to restricting intersections to protected left-turns need to assess the requirements of intersection capacity separately and crash history due to the conflict separately as well; then a judgment can be made as to whether a protected left-turn

may reduce crashes without necessarily increasing delay or affecting the traffic flow on the network. It is necessarily problematic when traffic flow and traffic safety performance measures are usually inverse to one another. Nonetheless, when compared to other alternatives discussed in this study, the effects of restricting intersections to protected left-turns may not be as significant on the traffic flow.

6.10.1.1 Advantages of Protected Left-turn

Protection offers greater security. However, it may only reduce statistically the frequency and severity of the consequences due to conflict and not necessarily eliminate them.

Advantages of restriction to protected left-turn include:

1. Reduced frequency of crashes
2. Reduced severity of crashes

6.10.1.2 Disadvantages of Protected Left-turn

Disadvantages of restriction to protected left-turn include:

1. Reduced green time available for other phases
2. Does not permit the usage of shorter cycle lengths, which may affect the overall delay and level of service of the intersection
3. Higher construction and maintenance cost as a longer left-turn lane is required to reduce the disruption of adjacent through lanes affected by long left-turn queues.
4. Higher construction and maintenance cost due to using actuated signalization of the intersection for best optimal results of the protected left-turn phasing

6.10.2 Grade-separated Left-turn

One of the best ways to reduce the number of conflicts on left-turns, while continuing to allow them is grade separation. This allows a smoother traffic flow and reduced delays. However, it can also be a financial burden to construct such intersections (interchanges). Nonetheless, weaving can become the consequence of grade separation when left-turn traffic merges on to the crossing traffic.

Grade-separation of a left-turn does not necessarily constitute an interchange. Some intersections can have only the left-turn grade-separated. The cost of grade-separating the left-turn is mainly determined on the type applied. An underpass is more costly than an overpass, when looking at the construction factors. However, it may be argued that by utilizing structures above the underpass may be more beneficial than the extra cost incurred during construction.

Re-construction of intersections to grade-separated left-turns requires a widening of the intersection footprint. That typically means acquiring additional right-of-way which adds to the project's cost and impacts, especially in the planning of the area.

6.10.2.1 Advantages of Grade-separated Left-turn

Advantages of restriction to protected left-turn include:

1. Reduced frequency of crashes
2. Reduced severity of crashes

6.10.2.2 Disadvantages of Protected Left-turn

Disadvantages of restriction to protected left-turn include:

1. Reduced green time available for other phases
2. Does not permit the usage of shorter cycle lengths, which may affect the overall delay and level of service of the intersection
3. Higher construction and maintenance cost as a longer left-turn lane is required to reduce the disruption of adjacent through lanes affected by long left-turn queues.
4. Higher construction and maintenance cost due to using actuated signalization of the intersection for best optimal results of the protected left-turn phasing

6.11 Other Design Alternatives for Enhancing Traffic Safety

Large intersections increase loss time due to longer clearance intervals, protected left-turn phasing, longer pedestrian clearance times, greater imbalances in lane utilization, and potential queue blockages caused by the resulting longer cycle lengths. Each of these issues suggests the need to investigate alternative methods to conventional lane additions in solving congestion-related problems. Essentially, not everything that is best for traffic flow is best for traffic safety and vice-versa. However, in general, the safer the roads, then accidents are less likely to occur. Consequently, the performance of the traffic flow is enhanced throughout by reducing any potential road hazards caused by the accidents.

There are different design alternatives for road intersections that include reconfiguration, at-grade indirect movements, and grade separation. The main purpose for many of those alternatives is to reduce conflict points, which provides safety and operational benefits by reducing the number of phases and conflicting volume at a single location. It is sometimes necessary to reconstruct the intersection in case low cost treatments, such as changing signal phases do not suffice.

6.11.1 Cost Efficiency of Left-Turn elimination vs. Grade-Separated left-turns

The construction of grade-separated left-turns is comparatively an expensive investment to other traditional at-grade solutions. Nevertheless, there is an alternative that is financially more appealing than grade-separated left-turns known as Continuous Flow Intersection (CFI).

Continuous Flow Intersection (CFI) is an at-grade intersection design that provides comparable level of vehicular flow to grade-separated interchanges at a fraction of the cost, and better long-term improvements over traditional at-grade approaches.

CFI works in a very simple manner by removing points of traffic conflicts at an intersection. Since one of the biggest conflicts at many intersections occurs when left-turning vehicles cross on-coming traffic, modifying intersection geometry to eliminate the left-turn conflict can considerably decrease delay to through vehicles. However, by separating conflict points, it is also advantageous to the traffic safety performance of the road.

6.11.2 How does CFI Work?

The main goal of CFI is to move the left-turn conflict out of the main intersection. In a typical CFI intersection, this is accomplished with a signalized left-turn bay placed several hundred feet before the intersection. The left-turn leg feeds a special CFI leg, which in turn empties into the cross street at another signalized intersection. The signals at the left-turn bay, CFI crossover, and main intersection are operated by single controller and coordinated to provide smooth traffic flow.

The following steps map the methodology for a left-turn in a CFI:

1. Step one: Enter the left-turn bay and stop at the first signal.
2. Step two: The signal at the CFI intersection is coordinated with the signal at the main intersection to optimize traffic flow. The signal at the end of the left-turn bay turns green (shortly after the cross traffic at the main intersection gets a green light). You cross the oncoming traffic lanes and proceed up the CFI leg. The right-turn lane merging with oncoming traffic will be on your left and through lanes themselves will be on your right.
3. Step three: Shortly prior to reaching the end of the CFI leg at its intersection with the cross street, the cross traffic gets a red light. The signal at the end of the CFI leg turns green and you complete your left turn onto the cross street without having to stop. The splendour of this arrangement is that the opposing traffic no longer has to be stopped to accommodate left-turning vehicles,

eliminating a signal phase and increasing the amount of through traffic moving during green time.

Studies have shown that CFI outperforms conventional alternatives dramatically. CFI improves the level of service of an intersection under existing traffic loads and reduces delay.

Some of the advantage of CFI intersections is that they save money on construction. CFI is certainly a flexible alternative. CFI can be arranged in a verity of geometries, including one-, two-, three-, and four-legged versions. Another attractive trait is that it does not require more right-of-way than a traditional at-grade intersection and substantially less than grade-separate intersections. However, CFI's main disadvantage is that it can reduce the access to existing businesses near the main intersection. Nevertheless, such an issue would still persist in a grade-separated intersection.

Further details on measuring performance of traffic safety are discussed in Chapter 7.

7. GIS Traffic Safety Analysis for Road Alternative Evaluations

7.1 Introduction

When given a set of different design alternatives of a road segment, there are two main issues that need to be looked at from a traffic engineering perspective, i) traffic flow performance, which determined by methods such as Level of Service (LOS), delays, turn penalties, (and others as stated in Section 3.5) and ii) traffic safety.

Traffic safety is quantified by determining the following factors:

a. fatalities
b. injuries
c. property damage

Traffic accidents are one of the top causes of fatalities in the world. Hence, it is a public health problem. Therefore, traffic engineers study the matter closely to determine the best method to avoid crashes. In this study, a performance indicator is constructed to quantify a performance index of traffic safety based on traffic conflicts.

Traffic movement conflicts occur primarily at intersections and weaving sections. There are mainly four main traffic movement conflict point types that exist, i) diverging, ii) crossing, iii) merging, and iv) weaving. There is a correlation between the severity of traffic crashes and the type of conflict point. Conflict points and traffic crashes has a correlation since a motorist can safely negotiate a limited number of conflict points

within a given area. Also, a correlation exists between traffic crashes involving areas of movement conflict points and traffic flow. For example, traffic flow characteristics, such as traffic volume and design speed are a major factor in determining the severity of traffic crashes based from conflict points.

7.2 Conflict Management

Initial attempts to quantify theoretical conflict opportunity surrogate to intersection annual crash prediction began with Perkins and Harris (1968), who introduced the concept of discrete conflicts in an intersection, such as angle, rear-end, and sideswipe conflicts. This concept was followed by other theoretical formulations. However, none of the early attempts were able to integrate individual conflicts to form an annual crash expectation involving each type of conflicts (Pugh and Halpin 1970, Baker 1972, Paddock 1974, Allen et. al. 1978, Zegeer and Dean 1978, Glauz and Migletz 1980, Horst 1990). However, a correlation was formulated for predicting crashes on passing conflict points on two-lane highway with annual crash records when calibrated with historical records (Kaub 1987).

Many studies have determined methods of managing traffic movement conflicts to enhance roadway safety. The following strategies have been found to reduce crashes based on conflict points:

a. limiting the number of conflict points that a vehicle experiences in its travel
b. separating conflict points as much as possible, if they cannot be eliminated

    c. removing slower turning vehicles from through traffic lanes as efficiently as possible

From the above strategies the following criteria that need to be included in the performance indicator of traffic safety based on traffic conflict points are deduced:

1. The density of traffic conflict points within a section of road.
2. The spacing between one conflict point and another.
3. The speed of both vehicles entering the conflict point.
4. The type of conflict point (i.e. diverging, crossing, or merging).
5. The approach angle of both vehicles with respect to each other.
6. The volume of traffic that share the conflict point.
7. The probability of crash.
8. The Time-to-Collision (TTC).
9. Expected severity of crashes.
    a. Fatalities
    b. Injuries
    c. Property damage
10. Signal phasing.

The above factors are used as base criteria to evaluate the performance indicator of traffic safety in accordance to traffic movement conflict points. These conflict points can either be within intersections, or also in freeway segments where weaving or other conflicts may occur. Next section discusses how these factors based on conflict points can directly affect the traffic safety performance of a road.

7.3 Relationship between Factors and Traffic Safety

The higher the density of conflict points, the more likely a traffic accident would occur. Hence, the less the spacing between one conflict and another directly affects the density of conflict points, and therefore the less the spacing between conflict points, the higher the likelihood for traffic collisions.

The speed of vehicles entering the conflict point has an interesting relationship with traffic collisions. For example, if there exists a crossing conflict point, then the severity of the crash is determined if the speed of one the vehicles is high, while the other vehicle is low. If both vehicles are traveling at high speeds, then it, theoretically, reduces the probability that both vehicles will be involved in a crash since the time frame that they both would be in the conflict point at the same time is reduced due to their traveling speeds. On the other hand, if both vehicles are moving at low speeds, then it either allows the drivers some time to try to maneuver to avoid collision or the severity of crash is reduced due to lower speeds. Deductively, if one of the vehicles is traveling at high speeds, while the other is traveling at lower speeds, then the vehicle traveling at lower speeds will be within the conflict point for a longer time and therefore increase the chance for the faster vehicle to collide with it. And since the collision is at high speed, the severity of the crash is high. Therefore, the relationship of speed of vehicles is determined by the relative speed between both vehicles. The higher the relative speed between both vehicles, the more likely there would be a collision and at an elevated severity.

The type of conflict point also determines the severity of a crash involved at that point. However, this relationship is mainly due to the approach angle of both vehicles with respect to each other. The angle is determined based on the difference angle of the axis from the travel path of the vehicles. In other words, the angle is the difference in the bearing of each vehicle.

To illustrate this notion, if the difference of bearings between the travel paths of the vehicles is 180^{o}, then it would mean a heads-on collision. Such can be assumed to be the most severe type of accidents. Therefore, it is assumed that the severity of the accident increases as the difference between bearing angles of the vehicles increase (limited up to 180^{o} of course). In merging points, the difference of bearing between vehicles is typically less than 90^{0}. However, for crossing points, it is determined mainly by the geometry of the intersection. In typical intersections, left turning vehicles have conflict points with difference of bearings between the vehicles between 90^{o} and 180^{o}.

Nevertheless, if having conflict points are inevitable in an intersection, the signal phasing plays a major role for understanding the critical probabilities. For example, if there exists an intersection with conflict points that are of high degrees, however the signal phasing for vehicles traveling through the conflict points are intermediated with another phase that would not have such a conflict point, then the probability for the vehicles entering the conflict point in question is drastically

decreased. Just as stated above, the probability is also determined by the volume of traffic for the vehicles entering the conflict point.

In many studies of traffic maneuver conflict points, the Time-to-Collision (TTC) is the most widely used factor to determine the safety of the roadway. TTC is defined by Hayward (1972) as the time it takes for the collision of two vehicles if they continue at their present trajectory at the same speed. When there is a collision course, the TTC-value becomes finite and is reduced with time. Therefore, the critical measurement in estimating the severity of the conflict is the minimum TTC during the conflict. There have been several studies that identify traffic safety impacts through the application of TTC distributions (Fancher et al. 1997, Van Arem and De Vos 1997). There are, however, variations to the TTC concept found in Hyden (1996) and Topp (1998) which include situations where no collision course prevails, but the time difference over a common spatial point is below a given threshold, usually fixed at 1.5 sec. These concepts are known as Post-Encroachment Times and Deceleration-to-Safety Time.

Recently, Minderhood and Bovy (2000) have developed two new safety indicators based on TTC that are useful to comparative road traffic safety analysis. The new method evaluates the indicators by using vehicle trajectories collected over a specific time period for a certain road segment to calculate a general safety indicator value. The classical method evaluates the traffic safety indicator at a specific cross-section.

The first of the new indicators developed by Minderhood and Bovy (2000) is the Time Exposed TTC, which measures the length of time that all vehicles involved in conflict points spend under a specific TTC minimum threshold during a determined time period. The second indicator is the Time Integrated TTC, which uses the integral of the TTC profile of drivers to express the level of safety over the determined time period. Both of those indicators together are used to derive mean values per vehicle and the probability of safety critical situations per time unit.

7.4 Avoidable Restrictions to the Model

There are several restrictions when modeling traffic safety measures. Driver behaviour is very difficult to predict. Therefore, as in any other model which can be used for a microscopic simulation, the data needs to be calibrated based on the average behaviour found in reality. However, since the model developed in this study is to compare traffic safety indicators based on conflict points between different road networks, it can be assumed that the drivers are equal. In other words, if comparing between a traffic intersection 'A' with another 'B', it is assumed that the diverse behaviour of drivers on each intersection is equally likely for comparative purposes.

Traffic flow analysis requires less consideration to driver behaviour and error modeling than traffic safety analysis. This is true because crashes are rare with respect to the amount of vehicle miles traveled. Therefore, the data for traffic flow is far more superior in quantity and quality compared to traffic safety data.

7.5 Traffic Safety Indicators Based on Conflict Points

7.5.1 Density of Conflict Points

The first factor to discuss, as stated previously, is the density of conflict points. For a road segment, such as an intersection or a weaving section, the density of conflict points is determined by the average space between one conflict point and another that a vehicle experiences over the total length of the segment. The total length of the segment is determined from the first point of conflict in the analysis to the last.

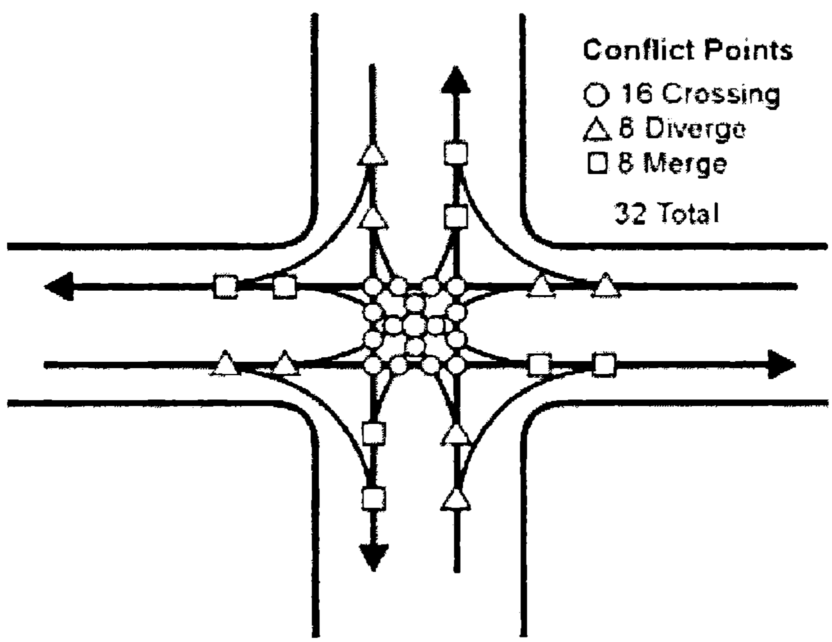

Figure 7.1 CONFLICT POINTS IN A TYPICAL INTERSECTION

As an example, *Fig. 7.1* illustrates conflict points in a typical intersection. There are 16 crossing, 8 diverging, and 8 merging points, giving a total

of 32 conflict points. However, when looking at the paths of vehicles, the maximum conflict points that a vehicle experiences is 2 diverging, 4 crossing, and 2 merging points. Such a path can be seen by the number of conflict points experienced by a through vehicle travelling westbound in *Fig. 7.2*. This is an example which is to be generalized to all travel paths in road segment under study.

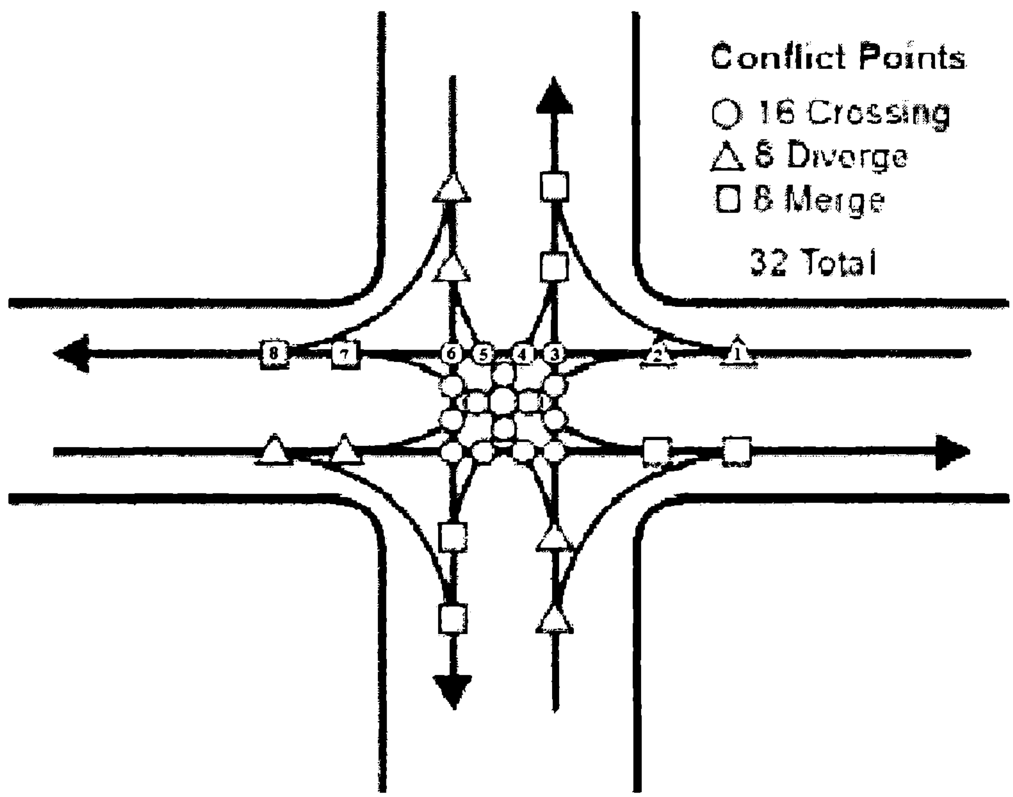

Figure 7.2 CONFLICT POINTS EXPERIENCED BY A VEHICLE TRAVELLING WESTBOUND

In *Fig. 7.2*, the distances between one conflict point and another for westbound traffic can be considered as follows, d_{12}, d_{23}, d_{34}, d_{45}, d_{56}, d_{67},

d_{78}. The density of conflict points (D_C) is therefore for the specific path is therefore,

$$D_C = \begin{cases} 1 + \dfrac{\sum CP_i}{\sum d_j}, CP > 1 \\ 1, CP = 1 \end{cases}, \qquad \text{(Eq. 7.1)}$$

where,

D_C	=	Density of conflict points
$\sum CP_i$	=	Total number of conflict points
$\sum d_j$	=	Total distance between conflict points.

7.5.2 Relative Speeds between Vehicles Entering Conflict Point, Volume, and Probability of Traffic Entering Conflict Point

As discussed earlier, the relative speed is important to determine the probability and severity of collision within a conflict point. As an example, if crossing traffic have the same speed, then theoretically, it is less likely to have a collision at Conflict Point 3 (CP3) in *Fig. 7.2*, since each crossing vehicle will remain in the conflict point for a short period of time due to the speed of each, when compared to the Conflict Point 8 (CP8), which is a merging point, as the merging traffic will be travelling at lower speeds than the through traffic. Therefore, the merging traffic will remain in the conflict point for a longer time due to its slow speed, giving a higher probability the through vehicle to rear-end the merging vehicle.

The volume of traffic sharing a conflict point also affects the probability of collision. As an example, defining the probability of vehicles entering a conflict point at the same time is based on the expected number of vehicles, which is determined by both the mean length of vehicles and the density, which in turn is based upon the flow rate and speed.

$$P(A) = \frac{l_1}{1000} \cdot D_1 \quad \text{(Eq. 7.2)}$$

$$D_1 = \frac{v_{p1}}{S_1} \quad \text{(Eq. 7.3)}$$

$$P(B) = \frac{l_2}{1000} \cdot D_2 \quad \text{(Eq. 7.4)}$$

$$D_2 = \frac{v_{p2}}{S_2} \quad \text{(Eq. 7.5)}$$

$$P(A \cap B) = P(A) \cdot P(B) \quad \text{(Eq. 7.6)}$$

P = Probability of vehicle entering conflict point at any given time

l = Average length of vehicle (m)

D = Density of traffic (veh/km)

v_p = Flow rate (vph)

S = Average speed of vehicles (kph)

The expected number of conflicts would therefore, be the average flow rate times the probability.

$$E(A \cap B) = v_p \cdot P(A \cap B) \quad \text{(Eq. 7.7)}$$

To illustrate an example, assume that the flow rate of two crossing traffic ***without*** any traffic controllers (freeflow) is 1500 vph, the average length of a vehicle is 5m, and the average speed is 80 kph. The total traffic flow entering the conflict point is therefore 3000 vph and the probability and expected number of conflicts is determined as follows:

$$P(A \cap B) = 0.008789$$
$$E(A \cap B) = 26.367$$

Hence, if no traffic controllers are assumed in an intersection with vehicles travelling at 80kph each, then there are about 26 crashes in an hour based on the above given data. To get more accurate data, field data collection is necessary to receive more actual numbers, which is also determined by the phasing timing of an intersection and the flow rate of vehicles running a red light, for example.

On the other hand, a different example of merging traffic in an unsignalized roundabout with a yield sign for entering vehicles is assumed. For such an example, an assumption may be made that the vehicles entering the roundabout is 15 kph with a flow rate of 1500 vph, the speed of vehicles inside the roundabout at the conflict point is 30 kph with a flow rate of 1500 vph, and the average length of all vehicles is 5 m. Therefore, the total flow rate entering the conflict point is 3000 vph and the probability and expected number of conflicts is determined as follows:

$$P(A \cap B) = 0.125$$
$$E(A \cap B) = 375$$

As illustrated in both examples above, it is determined what has been hypothesized that the slower the vehicles, the more time a vehicle remains within a conflict point and therefore the higher the probability for a collision to occur. However, as will be determined later, the severity of

crashes is mainly determined not by the number of conflicts, but by the approach angle of both vehicles with respect to each other and their speeds.

Reasonable to consider, an unsignalized roundabout has more plausible conflicts between vehicles entering the same point at the same time than a signalized intersection. However, since the type of conflict point in a roundabout is merging, and not crossing, and since the approaching vehicles are travelling at much lower speeds than at an intersection and therefore the relative approaching angle of both vehicles is smaller, then though there is a higher probability of a crash occurring in a roundabout, they are not usually severe. Most of which, if any, would cause minor damage (i.e. fender benders).

In conclusion to the effect of relative speed and traffic volume, the expected number of conflicts is therefore one of the mathematical factors to evaluate the traffic safety performance indicator based on conflict points.

7.5.3 Type of Conflict Point and Approach Angle of both Vehicles Entering Conflict Point with respect to Each Other

The difference of bearing angle between both vehicles entering a conflict point is important to determine the severity of the crash. The type of conflict point also has an important factor that determines the severity of a crash. For example, a diverging conflict point would mean that a vehicle diverging from through traffic would have to slow down to take a turn. This increases the chances for a rear-end crash. Usually vehicles

that take part of a rear-end crash have almost the same bearing. Therefore, the difference of their bearing is 0°. Also, through vehicles coming from behind the diverging vehicle would usually be able to have adequate sight distance and possibly be warned by the diverging vehicle through the use of turning lights. All this actually reduces the chances of a crash on a diverging conflict point.

On the other hand, if the type of conflict point is a crossing, then in most cases the difference between their bearings is 90° and above. Though, depending on the alignment of the approaches towards the intersection, there are possibilities to have crossing conflict points even lower. As concluded earlier, the greater the angle the higher the severity of the crash. Nevertheless, vehicles travelling on a crossing point may not always be aware of other vehicles crossing, especially in signalized intersections where one of the vehicles runs a red light. Hence, it increases the chances of a crash. Consequently, since awareness of other vehicles crossing is less and the difference between bearing angles is high, not only are the probabilities high for a crash, but also the crash would be more severe.

A merging conflict point usually has an approach bearing difference of less than 45° between conflicting vehicles. In many cases, the speed of a merging vehicle would be lower than crossing points, which would give adequate time for the merging vehicle to decide whether a passable gap exists to merge with the through traffic. Also, the difference between the approach bearing would be low, and therefore the probability of a crash

is low. If a crash would exist, then it is usually less severe than crossing points.

With the above given conditions, it is understood that the type of conflict point determines the amount of time drivers approaching the conflict point are aware of each other. The difference between approach bearing of vehicles (θ) establishes the type of crash, and therefore severity, which ranges from rear-end collision at 0^{o} to a heads-on collision at 180^{o}.

Unlike the difference between the bearing of conflicting vehicles, numerically, it is difficult to determine a mathematical factor for the type of conflict point. Thence, the suggested method is a percentage comparison in the number of crashes conceived based on statistical data of similar situations of conflicting points, if such data is not available for the intersection or road section under study. For example, such a percentage would be evaluated for the intersection in *Fig. 7.2* would be as follows:

a. Right-Turn Diverging (T_{RTD}) – similar to CP1 in *Fig. 7.2.*
b. Left-Turn Diverging (T_{LTD}) – similar to CP2 in *Fig. 7.2.*
c. Right-Turn Merging (T_{RTM}) – similar to CP7 in *Fig. 7.2.*
d. Left-Turn Merging (T_{LTM}) – similar to CP8 in *Fig. 7.2.*
e. Through-Through Crossing at start of intersection (T_{T1}) – similar to CP6 in *Fig. 7.2.*
f. Through-Through Crossing at end of intersection (T_{T2}) – similar to CP3 in *Fig. 7.2.*

g. Through-Left Crossing at start of intersection (T_{TL1}) – similar to CP4 in *Fig. 7.2.*
h. Through-Left Crossing at end of intersection (T_{TL2}) – similar to CP5 in *Fig. 7.2.*
i. Left-Left Crossing (T_L) – similar to CP9 in *Fig. 7.2.*

7.5.4 Expected Cost of Crashes

Cost of crashes is difficult to predict. The number of fatalities, injuries, and the amount of property damage may not always be known. Therefore, statistical data is used comparing similar types of conflict points that can be calibrated according to reality. To understand the share of the cost of each of the fatalities, injuries, and property damage is dependent on the value given for each. The total cost of accidents expected for a specific time period is evaluated as follows, in which the expected number of fatalities, injuries, and property damage can be taken from statistical data:

$$C = N(F)\cdot \overline{\mathrm{C}}(\mathrm{F}) + N(I)\cdot \overline{\mathrm{C}}(\mathrm{I}) + N(D)\cdot \overline{\mathrm{C}}(\mathrm{D}) \qquad \text{(Eq. 7.8)}$$

$\overline{\mathrm{C}}(\mathrm{F})$:	Average Cost of Fatalities
$\overline{\mathrm{C}}(\mathrm{I})$:	Average Cost of Injuries
$\overline{\mathrm{C}}(\mathrm{D})$:	Average Cost of Property Damage
$N(F)$:	Expected Number of Fatalities per Time Period
$N(I)$:	Expected Number of Injuries per Time Period
$N(D)$:	Expected Cost Number of Property Damage per Time Period

7.5.5 Signal Phasing

Signal phasing has a large effect on the safety of a signalized intersection. Not only is it capable of controlling traffic and therefore reduce the probability of conflicting vehicles, but also the actual order of the traffic phases can also reduce the likelihood of vehicles passing through the same conflict point.

In other words, if phase timings at a signalized intersection is ordered such that after the end of the green phase for through traffic from one street is followed by the start of green phase of through traffic from a perpendicular street, then there is a high probability of a vehicle running a red light and therefore enter the same conflict point of another vehicle, as in CP3 and CP6 in *Fig. 7.2*.

Conversely, if the end of the green time from the first street is followed by a green phase for right turning vehicles from the perpendicular street, the probability of vehicles entering CP3 and CP6 is significantly reduced, and the probability for entering CP8 would increase. However, based on the type and approach angle of vehicles in CP8, as well as the time-to-collision (TTC), would consider that in terms of traffic safety, it is of less a risk than CP3 or CP6.

Thence, it is evident that signal phasing, both all-red times and the order of phases, can significantly change the risks involved in conflict points by assigning different probabilities of two vehicles entering a conflict point. Evaluating this probability based on signal phasing is not intuitive.

Therefore, it is suggested using statistical data of the number of vehicles running a red-light form each signal phase. Consequently, those values like all others that are based on statistical data can be evaluated form other similar intersections and then calibrated by field data collection for a specific intersection.

As a result, mathematically, the factor for signal phasing can be evaluated as the number of vehicles running a red-light and passing through a conflict point with other vehicles. The more the vehicles that tend to run a red-light, the higher the potential of vehicles entering a conflict point. Since at signalized intersections, the volume of vehicles entering a conflict point is controlled, the possibility of vehicles entering the conflict point is determined by the volume of traffic running a red light against the volume of traffic with vehicles in the green phase. In other words, it is the evaluation of the probability that two vehicles enter a conflict point simultaneously.

As such, the mathematical expression is calculated similar to that in *Point #2* above. The only difference is determining the average number of vehicles running a red-light based on statistical data. It is not recommended to use a fixed factor, since running red-lights is determined by driver behaviour, which is different from one region to another, including the type of motorists travelling through a specific intersection within the same region, as well as the extent of law enforcement at a specific intersection (i.e. the presence of traffic police, red light cameras, etc).

7.5.6 Time-to-Collision (TTC)

Hayward (1972) defines TTC as the time required for two vehicles to crash if they continue at their present speed and bearing. Maneuvers that attempt to evade a collision are represented as the TTC at the onset of braking (TTC_{br}). The minimum TTC reached during the approach of two conflicting vehicles, TTC_{min}, indicates the severity of a potential conflict. In other words, this can be understood as the lower the TTC_{min}, the higher the risk of collision.

TTC is closely associated with *Point #2* above, as the same principles are used to evaluate mathematically. Nevertheless, TTC, in this sense, is mainly used for microscopic simulation purposes and is determined mainly by the sight distance between both arriving and opposing vehicles. If the sight distance allows for TTC >> TTC_{min}, then the indicator based on TTC,

$f_{TTC} = 1.0$, acting as an upper bound.

Otherwise, f_{TTC} is determined based on statistical data, the lower the TTC, the higher the probability of a crash. Therefore, f_{TTC} is a probability function of TTC for each conflict point. TTC is mainly considering the gap acceptance analysis, which is driver behaviour, and as stated earlier, is not vital when comparing between designs of different roadway sections or intersections, as it is assumed the same drivers travel the designed road. The time-to-collision is mainly under the influence of other factors that affect the traffic safety and evaluated in this study. Therefore, TTC does not immediately affect the results, and it

is left to the user to decide whether or not it is important to further evaluate it independently from other factors.

7.6 Consolidating Traffic Safety Indicators

Kaub (1996) has formulated a general form for quantifying typical conflicts with a good conformance to historical crash records as follows:

Conflict Opportunity(Type)$_t$ = *E(Movement Opportunities)*$_{ij}$ * *P(Arrival of Opposition to Movement)*$_{kl}$ (Eq. 7.9)

t = Specific Conflict Type, such as diverging, merging, etc.

i = Arrival Movement Type, such as the desire to pass, turning, changing lanes, etc.

j = Arrival Approach, such as one lane of a specific intersection approach which may have two or more approaches.

k = Opposition Movement Type, such as the vehicle opposing and entering the same conflict point, whether diverging, merging, intersecting, passing, etc.

l = Opposition Approach, such as the opposing specific lane in a multilane approach.

E(Movement Opportunities)$_{ij}$ = Expected number of vehicles per unit of time from a specific type "i," such as number of vehicles desiring to pass or turn on an approach to an intersection going into a conflict point, which may be exposed to an opposition movement on any particular roadway segment or intersection vulnerable to an opposition "j." The expectation, therefore, is formulated as follows:

E = P(Movement Opportunity / unit time) * (Vehicles performing this movement / unit time). (Eq. 7.10)

In most cases, the probability of movement opportunity may be 1.0, as the conflict may occur at any time. There are cases where the probability may occur at a discrete unit as where there exists a finite probability that a following vehicle may desire to pass on a two lane highway. Those probabilities are heavily related to the volume of traffic as discussed earlier.

P(Arrival of Opposition to Movement)$_{kl}$ = the probability of arrival of one or more vehicles during the specific time period of exposure to a particular type of conflict "k" or the probability of opposition during the time of exposure of the arriving vehicle to a conflict situation "k" on any roadway section or intersection approach or adjacent lane "l," where using the Poisson or similar distribution probability function follows the general form:

$$P(X \geq 1) = 1 - P(0) = 1 - \frac{e^{-m} m^{x}}{x!} = 1 - e^{-m}, \quad \text{(Eq. 7.11)}$$

where in conflicts:

m = arrival rate at conflict = [[q (veh/hr/lane/approach)] * [t (sec of exposure time)]] / 3600. (Eq. 7.12)

As the above is the general form suggested by Kaub (1996), it shall be used to integrate the factors for the indicators. As stated previously, the probability for movement opportunity is determined by the density volume of traffic entering the conflict point, whether at a roadway section or at a controlled intersection (i.e. signalized). However, this needs to be calibrated to the probability of crashes according to the type of conflict point "T_{x1x2}" (as stated in *Point #3* above), which is the percentage of crashes expected.

$$P(A) = \frac{l_1}{1000} \cdot D_1$$

$$D_1 = \frac{v_{p1}}{S_1}$$

$$P(B) = \frac{l_2}{1000} \cdot D_2$$

$$D_2 = \frac{v_{p2}}{S_2}$$

$$P(A \cap B) = P(A) \cdot P(B) \cdot T_{x_1 x_2}$$

The density (D) is determined by the volume and speeds of each approaching lane entering the conflict point. However, it is important to note that for uncontrolled approaches towards the conflict point, the traffic flow is continuous by both approaches, in which it is likely for vehicles to enter the point at any time. However, in controlled entry to conflict points, such as signalized intersections, the density for one movement is limited to the traffic flow of vehicles running a red light within the width of the conflict zone against opposing traffic density. Therefore, as noted earlier, the expected number of vehicles (both

arriving and opposing) entering a conflict point, Conflict Opportunity(Type)$_t$ is

$$E = E(A \cap B) = v_p \cdot P(A \cap B).$$

Now the above gives the expected number of crashes calibrated based on statistical data according to the type of conflict, which is mainly determined by the type of conflict point between both arriving and opposing vehicles.

Severity of crashes is determined mainly by the approach angle of conflict (θ) and speed of entering vehicles. Although speeds have already been used to determine the density of traffic, it is necessary to use the relative speeds to resolve the severity of conflict. In terms of speeds and approach angle of conflicts, the indicator for the severity of crashes can be compared as follows:

$$f_s = S_1 \cdot S_2 \cdot \theta. \qquad \text{(Eq. 7.13)}$$

Expected cost of crashes, as stated earlier, is given by Eq. 7.8 as

$$C = N(F) \cdot \overline{\mathrm{C}}(\mathrm{F}) + N(I) \cdot \overline{\mathrm{C}}(\mathrm{I}) + N(D) \cdot \overline{\mathrm{C}}(\mathrm{D}),$$

which can be calibrated according to statistical data for both the average cost and expected number of fatalities, injuries, and property damage.

To further calibrate the performance indicator, the probability function of TTC, f_{TTC}, is assessed based on statistical data.

Thence, for each conflict point, the safety performance indicator per conflict point is as follows:

$$PI_i = E \cdot C \cdot f_s \cdot f_{TTC} \qquad \text{(Eq. 7.14)}$$

Nonetheless, the safety performance indicator for a group of conflict points is determined by its density. Based on the example shown formerly in *Fig. 7.2*, westbound traffic undergoes eight conflict points. Each conflict point has an individual PI_i. Consequently, the density is based on the interval of a vehicle passing one conflict point to the other, as the more a vehicle passes between conflict points, the less attentive the drivers are to each conflict point, and such is evaluated as follows from Eq. 7.1:

$$D_C = \begin{cases} 1 + \dfrac{\sum CP_i}{\sum d_j}, CP > 1 \\ 1, CP = 1 \end{cases}.$$

As a result, the safety performance indicator for a group of conflict points per vehicle path is expressed as follows:

$$PI_j = \sum_i^m PI_i \cdot D_C. \qquad \text{(Eq. 7.15)}$$

Conclusively, the safety performance indicator based on conflict points on any given roadway section or intersection for "*n*" number of lanes on all approaches is given by

$$PI = \sum_{j=1}^{n} PI_j \, . \qquad \text{(Eq. 7.16)}$$

The safety performance indicator, *PI*, is evaluated in units of cost per unit of area. This follows the logic of how much do crashes cost per unit of area in a roadway segment or intersection.

7.7 Example for Suggested Model

An example is constructed assuming an uncontrolled intersection, to dramatize the traffic safety measure, as shown in *Fig. 7.3* earlier and traffic flows as in *Fig. 7.4* below.

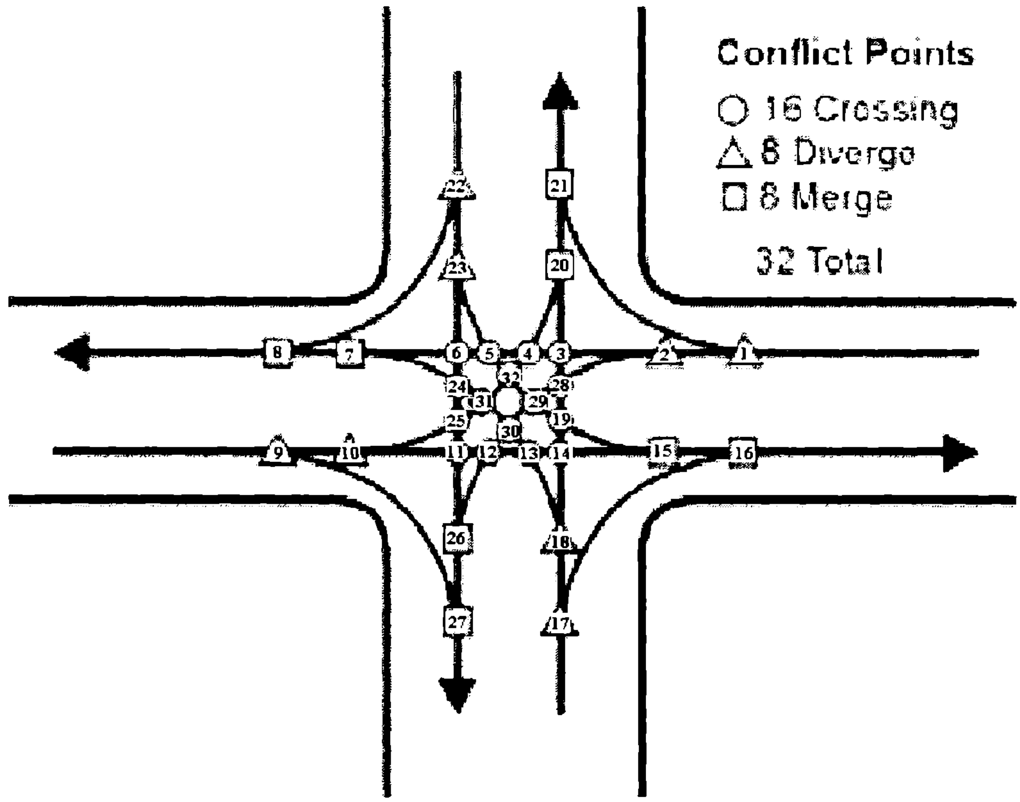

Figure 7.3 INDEXED TRAFFIC CONFLICT POINTS

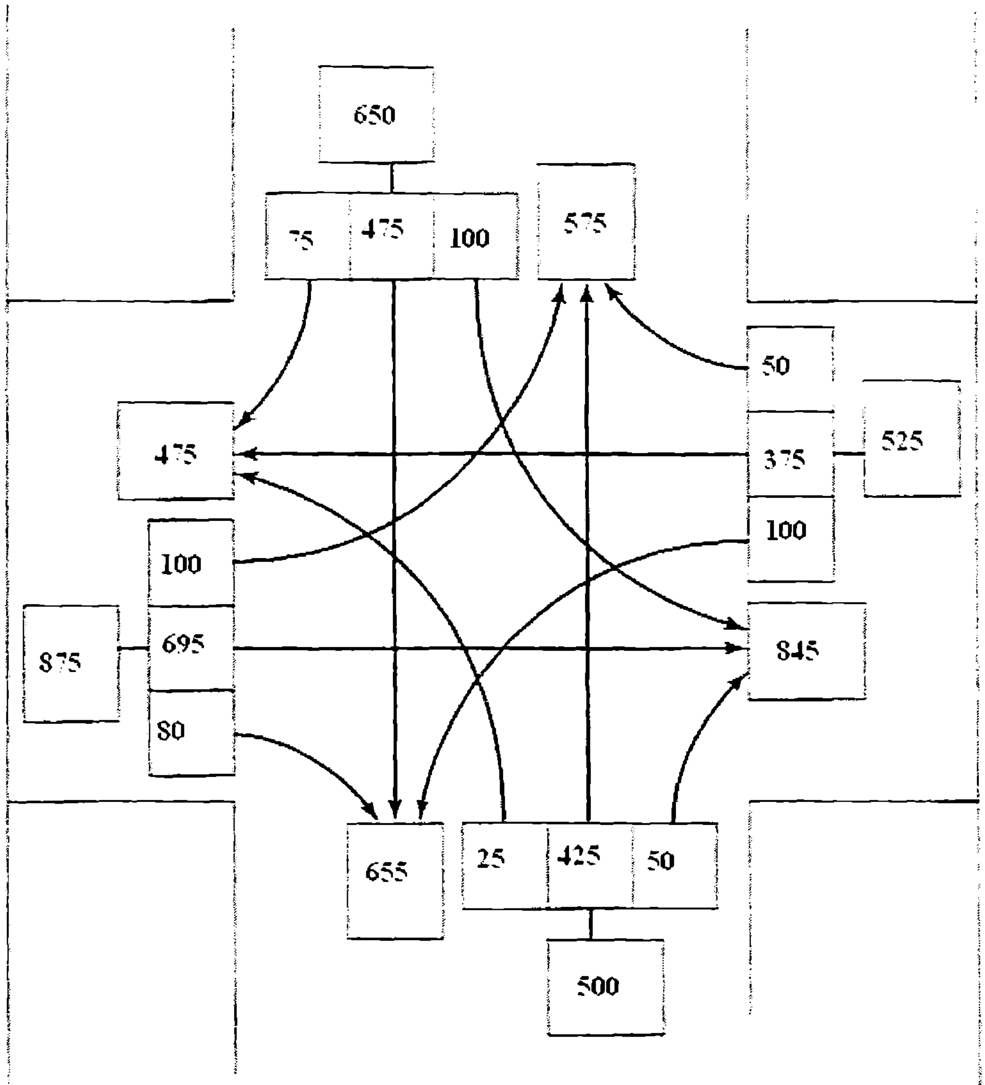

Figure 7.4 TRAFFIC FLOWS

The average length of a vehicle is assumed to be at 5.5m. *Table 7.1* below defines the assumed approach speeds, the density, and probabilities using the following equations:

$$P(A)=\frac{l_1}{1000}\cdot D_1$$

$$D_1=\frac{v_{p1}}{S_1}$$

$$P(B)=\frac{l_2}{1000}\cdot D_2$$

$$D_2=\frac{v_{p2}}{S_2}$$

$$P(A\cap B)=P(A)\cdot P(B)\cdot T_{x_1x_2}$$

Table 7.1 Approach speeds, density, and probabilities

	Approach 1			Approach 2			Approach 3			Approach 4		
	LT	TT	RT	LT	TT	RT	LT	TT	RT	LT	TT	RT
Speed (kph)	30	70	25	30	70	25	30	70	25	30	70	25
Traffic Flow (vph)	100	375	50	100	475	75	100	695	80	25	425	50
Density (vpk)	3.33	5.36	2.00	3.33	6.79	3.00	3.33	9.93	3.20	0.83	6.07	2.00
Probability	0.02	0.03	0.01	0.02	0.04	0.02	0.02	0.05	0.02	0.00	0.03	0.01

The approach angle is summarized in *Table 7.2*, according to the type of control point.

Table 7.2 Bearing difference of approaching vehicles into conflict points

CP Type	Bearing Difference (Degrees)
RTD	20
LTD	20

CP Type	Bearing Difference (Degrees)
RTM	20
LTM	20
T1	90
T2	90
TL1	70
TL2	110
L	90

The costs of fatalities, injuries, and property damage are given in *Table 7.3* below.

Table 7.3 Costs of crashes

Average Cost of Fatalities =	$800,000	
Average Cost of Injuries =	$10,000	
Average cost of Property Damage =	$20,000	
Expected Number of Fatalities =	0.375	(assumed constant for all CP)
Expected Number of Injuries =	1.125	(assumed constant for all CP)
Expected Number of Property Damage =	2.25	(assumed constant for all CP)
Cost of Crashes =	$356,250	
Index for Cost of Crashes (in millions) =	**$0.35625**	

Table 7.4 summarizes the performance indicator PI_i for each conflict point using Eq. 7.14

$$PI_i = E \cdot C \cdot f_s \cdot f_{TTC} .$$

Table 7.4 Summary of performance indicator for each conflict point

CP	Type	Calibration Probability (Txx)	Crash Probability P(A ∩ B)	Combined Density	Expected Conflict E(A ∩ B)	Bearing Difference (Degrees)	*fs*	fTTC	PIi
1	RTD	0.02	6.48214E-06	7.36	4.76901E-05	20	35000	1	0.59
2	LTD	0.02	1.08036E-05	8.69	9.38882E-05	20	42000	1	1.40
3	Tx	0.03	4.82688E-05	15.29	7.37823E-04	90	441000	1	115.92
4	TL1	0.05	2.70089E-05	8.69	2.34720E-04	70	147000	1	12.29
5	TL2	0.05	6.75223E-06	6.19	4.17995E-05	110	231000	1	3.44
6	Tx	0.03	2.95169E-05	11.43	3.37336E-04	90	441000	1	53.00
7	LTM	0.02	1.08036E-05	8.69	9.38882E-05	20	42000	1	1.40
8	RTM	0.02	6.48214E-06	7.36	4.76901E-05	20	35000	1	0.59
9	RTD	0.02	1.23161E-05	6.80	8.37766E-05	20	35000	1	1.04
10	LTD	0.02	1.36845E-05	10.12	1.38474E-04	20	42000	1	2.07
11	Tx	0.03	3.73881E-05	12.86	4.80704E-04	90	441000	1	75.52
12	TL1	0.05	3.42113E-05	10.12	3.46186E-04	70	147000	1	18.13
13	TL2	0.05	3.42113E-05	10.12	3.46186E-04	110	231000	1	28.49
14	Tx	0.03	6.11405E-05	16.71	1.02192E-03	90	441000	1	160.55
15	LTM	0.02	3.42113E-06	7.62	2.60658E-05	20	42000	1	0.39
16	RTM	0.02	1.31371E-05	9.99	1.31184E-04	20	35000	1	1.64
17	RTD	0.02	1.92217E-05	13.13	2.52354E-04	20	35000	1	3.15
18	LTD	0.02	2.00226E-05	13.26	2.65538E-04	20	42000	1	3.97

CP	Type	Calibration Probability (Txx)	Crash Probability P(A ∩ B)	Combined Density	Expected Conflict E(A ∩ B)	Bearing Difference (Degrees)	*fs*	fTTC	PIi
19	TL1	0.05	1.25141E-05	10.76	1.34676E-04	70	147000	1	7.05
20	LTM	0.02	2.00226E-05	13.26	2.65538E-04	20	42000	1	3.97
21	RTM	0.02	1.20136E-05	11.93	1.43305E-04	20	35000	1	1.79
22	RTD	0.02	7.34643E-06	8.07	5.92962E-05	20	35000	1	0.74
23	LTD	0.02	3.06101E-06	6.90	2.11356E-05	20	42000	1	0.32
24	TL1	0.05	3.06101E-05	9.40	2.87881E-04	70	147000	1	15.08
25	TL2	0.05	3.06101E-05	9.40	2.87881E-04	110	231000	1	23.69
26	LTM	0.02	1.2244E-05	9.40	1.15152E-04	20	42000	1	1.72
27	RTM	0.02	1.10196E-05	9.07	9.99639E-05	20	35000	1	1.25
28	TL2	0.05	5.00565E-05	13.26	6.63845E-04	110	231000	1	54.63
29	L	0.04	3.36111E-06	4.17	1.40046E-05	90	81000	1	0.40
30	L	0.04	1.34444E-05	6.67	8.96296E-05	90	81000	1	2.59
31	L	0.04	1.34444E-05	6.67	8.96296E-05	90	81000	1	2.59
32	L	0.04	3.36111E-06	4.17	1.40046E-05	90	81000	1	0.40
TOTAL		**1.00**	**6.17982E-04**	**307.56**	**7.01317E-03**				

There are essentially twelve paths, four through, four right-turns, and four left-turns, which are needed to follow to obtain the final performance indicator for the whole intersection (design). The density of conflict points for each path is assumed constant for the path type and assumed in *Table 7.5*.

Table 7.5 Density of conflict points according to path type

	Dc (CP/m)
T	0.25
R	0.1
L	0.2

Table 7.6 gives a summary of the paths sequence.

Table 7.6 Paths

Path	**Type**	**Sequence**							
1	T	1	2	3	4	5	6	7	8
2	T	9	10	11	12	13	14	15	16
3	T	17	18	14	19	28	3	20	21
4	T	22	23	6	24	25	11	26	27
5	R	1	21						
6	R	9	27						
7	R	17	16						
8	R	22	8						
9	L	1	2	28	29	30	12	26	27
10	L	9	10	25	31	32	4	20	21
11	L	17	18	13	30	31	24	7	8
12	L	22	23	5	32	29	19	15	16

Finally, based on all the matrices above, the final performance indicator,

PI = 0.2729 $/km^2 (in millions of dollars) as shown in *Table 7.7* or PI = 0.2729 $/m^2.

Table 7.7 PI result

Path	∑Pli	Dc (CP/km)	Pij		
1	188.64	0.00025	0.04716		
2	287.83	0.00025	0.07196		
3	351.03	0.00025	0.08776		
4	171.31	0.00025	0.04283		
5	2.38	0.0001	0.00024		
6	2.29	0.0001	0.00023		
7	4.78	0.0001	0.00048		
8	1.33	0.0001	0.00013		
9	80.72	0.0002	0.01614		
10	47.85	0.0002	0.00957		
11	57.86	0.0002	0.01157		
12	14.38	0.0002	0.00288		
		PI =	**0.29094**	**$ / m**	**(in millions)**

7.8 Conclusion

Traffic safety is highly determined by the number, type and density of conflict points. It is also determined by the relative bearings of vehicles entering the conflict points and their speeds. It is usually simple to quantify a performance indicator based on traffic flow, but few performance indicators exist for traffic safety. It has been presented a methodological mathematical expression to quantify a performance indicator that allows departments of transportation, traffic authorities, and researchers to compare the safety of traffic between two or more designs of a roadway segment or intersection.

In most cases, traffic engineers and researchers focus more on comparing traffic flow between different designs, and rarely, if ever compare traffic safety. This is probably due to the difficulty evaluating and quantifying a performance indicator for safety and the priority to enhance Levels of Service (LOS) by reducing traffic delay.

This study has attempted to simplify a comparable value for traffic safety based on conflict points and integrated the different factors that measure this performance indicator between different designs. The performance indicator does not attempt to predict the number of accidents expected annually. It is only meant as a measure for comparison purposes of traffic safety.

8. Construction Analysis of Roads Alternatives

8.1 Introduction

Construction is the epitome of rigorous planning and decision-making. It is the key to development that throughout history was a sign of human civilization. Human beings have been able to construct wonders throughout the world. The main obstacle to any construction is not the topography of an area, as nothing is impossible. The true hindrance is budget. To any decision-maker the words construction and cost are almost synonymous.

With different road design alternatives, costs vary widely. Different factors determine the performance of construction including i) cost, ii) length of time for construction completion, and iii) flexibility of construction. These factors are comparable between different alternatives. However, there are other factors in construction that would be similar to any of the alternatives and therefore, are not considered in this study. For example, the impact of weather conditions on construction operations are not unnoticeable to the planning and scheduling of the construction. Nevertheless, the impact will be the same regardless of the alternative chosen.

Estimating costs is not an easy task. Not only is it difficult to assess the cost of the right-of-way, in the current situations, the cost of construction materials is very volatile as it is affected by domestic and international markets. As many countries boom in the construction industry, the costs

of materials usually rise due to increased demands. Knowing the fact that time is required from the planning stage to the actual construction, the cost of construction would increase due to the volatile nature of the cost of materials and the natural increase in prices due to inflation. In addition to this, there are a number of uncertainties that which may include not only the cost of construction, but also uncertainties of what are required during construction.

During the construction of the 'Big Dig' project in Boston, Massachusetts, there were many uncertainties that have arisen due to surprises found at the site of construction. Since the project is mainly built on what used to be a landfill, there has been much debris underground that included wreckage of sunken ships, which were not part of the initial assessment.

Evaluating the uncertainties and their related costs is therefore not simple. However, when evaluating different alternatives, there is a possibility to conclude that some alternatives may share the same uncertainties, which actually help in the comparison process. Since this research is mainly focused on evaluating different alternatives to compare and rank those alternatives, it is not necessary to have a full understanding of the uncertainties associated with each. For example, if there are two alternatives for a roads construction, the potential of the increase in the cost of material would be similar for either alternative. Also, since alternatives are usually in a geographically similar area, the majority of the uncertainty would be comparable.

8.2 GIS Data Acquisitions for Estimating Construction Cost

From a construction perspective, there are three main branches for cost, i) cost of construction, ii) cost of mitigation, and iii) cost of maintenance. The geographic location of a project is responsible for many of the factors pertained in the cost of construction. However, since the main objective of this study is to have a comparison between different alternatives, the geographic area of those alternatives would usually lie in the same area, and therefore the geographical factors in the cost of construction would be widely shared between them. Therefore, the factors of geography are downplayed in this study.

Fan et al. (2001) have argued that acquiring and analyzing spatial data are perceived as a time-consuming process and susceptible to certain biases. There have been several methods proposed to estimate cut-and-fill quantities accurately (Siyam 1987, Epps and Corey 1990, Easa 1992). Stark and Mayer (1983) have also proposed methods to optimize earthmoving operations. As these studies have been done during a time that technology for GIS has not been easily accessible, certain limitations existed in the models.

With the advances in 4D CAD technology and its successor, 4D CAD GIS (Galadari 2003, Galadari 2004) many of these limitations have been addressed, such as i) database population, ii) constructability factors, iii) 3D visualization and 4D simulation, and iv) scheduling capabilities.

4D CAD GIS does not only address constructability factors of the structures, but also obstructions encountered during earthmoving activities as well. For example, the current topography, whether natural or man-made, may act as an obstacle to the construction. Thus, GIS is used to generate spatial analysis that allows for optimum earthmoving plans using mass haul diagrams. It is naturally imperative to have a digital terrain model (DTM) as one of the major geographic features necessary to evaluate the cost of construction. Also, having geologic and geomorphologic data is important to further estimate the cut and fill quantities and understand the cost of earthmoving activities.

Visualization of construction projects facilitate decision making processes during design and implementation of a project. 4D CAD links 3D digital models with construction activities and used by planners, designers, and engineers to analyze and visualize various phases of a project such as design related decisions, construction planning, cost, and availability of resources (McKinney and Fisher 1998). The usage of such tools is imperative due to the relationship between construction scheduling with time and cost of a construction project. Though 3D geometry allows the visualization of a structure, it seldom provides details of various complex components pertaining to the design that is accompanied by the construction schedule, such as understanding the impact of expected and unexpected delays or conflicts that would undermine the completion of the project on-time (McKinney and Fisher 1998).

A relationship between the GIS data and the work-breakdown structure (WBS) is developed to replicate construction job logic. The relational database within a GIS environment would not only have the capability to dynamically interact between geographic data and work scheduling but also to store and analyze swell and shrinkage of soil types in the area in question.

As an advantage, it is safe to conclude that due to the repetitive nature of the roads construction activities, the GIS has the capability to work on a resource-driven scheduling engine. Within a GIS framework, mass haul diagrams (Stark and Mayer 1983) can be further enhanced to take into consideration the presence of different subsoil strata in cut sections, topographic obstructions, and variability in soil compaction. The digital terrain models (DTMs) are stored in triangulated irregular networks (TINs) (Oloufa 1991).

Through the usage of borehole data, a full three-dimensional visualization of the soil strata is achieved using interpolation of the stratum of each soil type. Epps and Corey (1990) have proposed an average-end-area method to be utilized to estimate volumes of soil strata and to estimate volume in curved portions (Easa 1989b, Easa 1992) and the outcome of such a process allows for the evaluation of the cost of earthmoving operations. This method allows for an automated process to populate the GIS database with necessary information to understand the related costs of construction.

According to Alkass and Harris (1991), obstructions due to topographic features play a major role in performing WBS. Two types of obstructions have been defined, i) surmountable, where access is granted across the obstruction at an overhead (i.e. time and cost), and ii) insurmountable, where no access is granted or that which access is not feasible during the time of construction (i.e. passing through a protected archaeological site).

A precedence network is generated detailing operations along the main project route as well as the construction of overpasses, underpasses, and interchanges. Through the generated WBS, a selection of activities generates the precedence network.

8.3 Estimating Construction Cost

From a construction perspective, there are three main branches for cost, Understanding how to predict road construction costs is important when evaluating the various alternatives. Different methods exist for forecasting future highway construction costs. Some traditional methods have been found unreliable, such as estimating the short-term cost in unit of currency per distance (Hartgen and Talvitie 1995, Stevens 1995). Other methods, such as time-series analysis has also been used to forecast future construction costs (Koppula 1981, Hartgen et al. 1997).

Accurate early cost estimates for construction are extremely important to any organization (Oberlander & Trost 2001) and therefore, can directly influence regretting the decisions made as to which alternative is best. Budget estimates usually have two main components, baseline estimate

and cost contingency, which together represent the estimated final cost of the project. Thence, the accuracy of estimating construction cost is crucial to any project, and if the reliability is a problem, will affect the probability matrix of the regret model, causing a wider range for regret. Estimating the cost contingency that is given for each alternative compared is very important to ensure that the amount of regret is reduced by better expecting the amount of cost overruns.

Merrow and Schroeder (1991) have shown the link between predicting cost growth and cost contingency. Their research have shown that there is no direct link between cost growth and contingency, although one might have expected that the contingency is there due to cost growth of the construction. This is mainly due to the fact that cost contingency is possibly the most misunderstood word in project execution (Patrascu 1988). It is defined as the amount of funds, budget, or time required over the estimate to reduce the risk of overruns of project objectives to acceptable levels (PMI 2004).

There are four main attributes that constitute the contingency cost in estimating construction budgets, i) reserve, ii) risk and uncertainty, iii) total commitment, and iv) project behaviour. According to Baccarini (2005), reserve is the most understood component of project cost contingency, as it is defined as a reserve of money (PMI 2004).

Since regret is mainly due to risks and uncertainties, the amount for contingency reflects the existence of such in projects (Thompson and Perry 1992). Hence, the provision of cost contingency is an attempt to

make a risk management tool that would constrict the amount of regret expected form the overrunning the cost. Since the budget is based on the baseline and contingency, then it classifies the reduction of risk and uncertainty based on the total financial commitment within the budget estimates, allowing for further reliability of the amount of regret. In regards to the project behavior, Dev et al. (1994) have concluded that contingency appropriation need not to be too high allowing for poor cost management, nor too low resulting in unsatisfactory performance outcomes.

There are many cost estimation models that exist for budgetary purposes, in which the reliability of the values are coherent, such as traditional percentage (Ahmad 1992, Moselhi 1997), method of moments (Diekmann 1983, Yeo 1990, Moselhi 1997), Monte Carlo simulation (Lorance and Wendling 1999, Clark 2001), factor rating (Hackney 1985, Oberlander and Trost 2001), individual risks expected value method (Mak, Wong and Picken 1998, Mak and Picken 2000), range estimating (Curran 1989), regression analysis (Merrow and Yarossi 1990, Aibinu and Jagboro 2002), artificial neural networks (Chen and Hartman 2000, Williams 2003), influence diagrams (Diekmann and Featherman 1998), theory of constraints (Leach 2003), and analytical hierarchy process (Dey, Tabucanon and Ogunlana 1994). Traditional percentages are the most widely used method of estimation in practice, but other methods have gained prominence recently, such as Monte Carlo simulation, regression analysis, and artificial neural networks (Baccarini 2005).

The traditional percentages method is a deterministic approach of estimation based on most likely values (Mak et al. 1998). This estimating method is arbitrary and difficult to justify (Thompson and Perry 1992), as it is based on an added percentage on the baseline cost derived from intuition, experience, and historical data. According to Hartman (2000), it is an unscientific approach and a reason why many projects are over budget. Therefore, it is believed that this method will give a very low probability for a positive outcome in the probability matrix in the regret model. However, it can easily compute the amount of probability value in the matrix based on statistical data, and since the regret model only considers consistency in the model used to identify the performance indicators, it can be easily seen that the probability of having accurate costs is consistent for the alternatives being evaluated, and therefore the final results would, therefore, be insensitive to the amount of error produced in comparison between one alternative and the other.

Monte Carlo simulation is a quantitative technique for analyzing risk and provides a structured method of setting values in project cost estimates (Clark 2001). The output of the simulation is a probability distribution which can be entered into the probability matrix of the regret model.

Artificial neural networks is a problem-solving method that mimics the interconnection of brain neurons for information processing that allows detection of hidden relationships among data and generalizing solutions to new problems (Chen and Hartman 2000). Using this method, Chen and Hartman (2000) have found that 75% of the predicted final cost aligned with the actual variance. The prediction accuracy of this method

has been found to outperform multiple linear regressions. This can therefore also be included within the probability matrix.

Regression models is a powerful statistical tool to analytically predict overall estimate reliability of cost estimation (Kim et al. 2004). However, in a comprehensive review in the usage of cost modeling techniques by Skitmore and Patchell (1990), it has been found that regression analysis has been mainly used for predicting tender prices and not the actual client's final cost. Regression analysis for cost modeling follows the principle of parsimony, which means that models should be simple and fit the data adequately without using unnecessary parameters to produce better cost forecasts (Sonmez 2004, Cheung 2005).

Merrow, Phillips and Myers (1981) conducted a research of the reliability of cost estimation using regression analysis. It has been found that only about 47% of the estimates were predicted within 5% of the actual cost growth. Bacon and Besant-Jones (1998) investigated the reliability of estimates of construction costs. The research found that estimated values were significantly biased below actual costs, with squared correlations between the actual and estimated costs of 76% and an average estimation of 21% with a standard deviation of 34%.

In an attempt to predict the amount of inaccuracy in the cost estimation to determine the amount of cost contingency, Oberlander and Trost (2001) developed a model using regression analysis that predicts the amount of contingency cost required based on the quality and accuracy of the project's cost estimate. They have found that there is a significant

correlation between the estimate score and the accuracy of the estimate. Therefore, in estimating the budget, the model quantifies the accuracy of the cost estimate, the greater the inaccuracy, the more contingency for a chosen confidence level is appropriated, bringing the total cost of the construction to a more accurate estimate. The accuracy of their model has been shown to be greater than 60%.

Williams (2002, 2003) used regression analysis to predict actual cost of competitively bid highways project, based on 3444 projects. A natural log transformation and stepwise regression procedure yielded a best performing predictive model for actual cost based on one independent variable. The models were tested using independent data sets that were not used to calculate the regression model. Between 69% and 77% of projects were predicted within 10% of the actual costs.

Odeck (2004) investigated the statistical relationship between actual costs and estimated costs of 620 road construction projects. The research divulged a discrepancy between estimated and actual costs with a mean cost growth of 7.9% ranging from -59% to +183%. The cost growth appeared to be predominant among smaller projects compared to larger projects, which is only mathematically natural. The stepwise regression model used in the research classified two significant variables, estimated cost and time of completion, especially since cost growth is highly dependent on time.

Kim, An and Kang (2004) developed a prediction model for cost estimates based on the construction of 530 residential buildings. The

research has found that the mean absolute error of the model was 6.95%.

Burroughs and Juntima (2004) developed a contingency performance indicator, based on the difference between the absolute value of percent for contingency used and the percent of contingency estimated. The formula was derived based on 1500 projects. The model was built based on five significant independent variables, project definition level, use of new technology, process complexity, contracting and execution strategy, and equipment percentage. The model produced a median performance indicator of 7%.

8.4 Estimating Long-Term Cost

Understanding the economics of construction requires the identification of the initial cost of construction and mitigation with the annual maintenance and re-pavement costs. There are several models that provide quantitative analysis for cost versus benefit over the life-cycle of the road. However, it is important to note that the physical life-cycle of a road may not necessarily coincide with the life expectation of the traffic flow that the road has been designed to meet its requirements. Hence, it is important to take into account the flexibility of the road construction and future expandability.

The US Department of Transportation (2002) has developed a tool that evaluates the life cycle cost analysis (LCCA) model, which is used to compare user and agency costs of competing alternatives of road construction projects. LCCA is one of the major components of a benefit-

cost analysis that compares the benefits and costs in selecting an optimal alternative (AASHTO 2003). The following steps have been found to be essential:

1. Establish objectives
2. Identify constraints and specify assumptions
3. Define base case and identify alternatives
4. Set analysis period
5. Define level of effort for screening alternatives
6. Analyze traffic effects
7. Estimate benefits and costs relative to base case
8. Evaluate risk (and regret)
9. Compare net benefits and rank alternatives
10. Make recommendations

LCCA, however, is only beneficial if different alternatives would yield equal benefits (Kirk and Dell'Isola 1995). Though this is not assumed in the approach of this study, it is important to note that since the performance indicator that pertains to construction is not the only indicator that would be taken into consideration, results for using such a model would still be possible even if the model assumes equal benefits. LCCA is mainly developed to be a sole indicator of the decision to be made. However, it is possible to consider it as part of the many indicators used in this study.

One of the challenges that face the evaluation of decision analysis is comparing values of different units, even if the comparison is stated in

monetary units of currency for two main reasons, i) inflation and ii) discounting. Inflation causes the purchasing power of currency to change over time. This is especially seen in the Big Dig project in Boston, and the building of a highway corridor in Plzeň, Czech Republic. Therefore, if a roads project is proposed, then it is important to note the duration of the project when comparing alternatives, because the present value of each of them would be different dependent on the construction duration. In other words, this comparison represents the difference between real and nominal cost of a project alternative, where the real cost is the actual payments made, whereas the nominal cost is the actual present value based on the purchase power due to inflation. For example, if there are two different road alternatives, one which would complete within a 2-year time period, while the other within a 5-year time period, then comparing the initial costs of each would not be as direct as one might consider. Since the payment scheduling would be different, then the present value of each cost need to be evaluated, and it is the present value that would need to be compared more specifically and included within the performance indicator. Similarly, the life cycle and annual maintenance cost would need to be evaluated for its present value for comparison purposes. It is important to be reminded that the life cycle does not necessarily mean the physical life of the road, but the traffic adequacy of the road, since its design may need to be changed in the future due to increased traffic flow or to improve traffic safety, such as those studied in the reconstruction of highway interchanges in Dubai, UAE. The expandability of the road is also crucial as noted earlier and evaluated in a similar economical manner.

For example, if a road is expandable in the future, it is important to note the net present values of the i) initial cost, ii) the annual maintenance cost over the period until it is to be expanded (or reconstructed), iii) the cost of expansion (or reconstruction), iv) and the annual maintenance cost after expansion (or reconstruction) for the remaining period of the life cycle, either based on physical life or traffic life. In many cases, the expansion and even reconstruction is planned for the future during the initial road design and the flexibility of such designs are laid out. There could also be subsequent expansions or reconstruction made as well.

Critical to note that the salvage value, in cases of reconstruction, need to also be noted and evaluated as part of the net present value when comparing different alternatives. The salvage value is the residual value of the materials that may be re-used or recycled. Hence, using construction materials that may be reused or recycled, and therefore, depreciates less and have a better salvage value, may also provide a better value for the construction performance indicator.

Generally, the net present value would include as many factors as required or available. The net present value is expressed in the following form:

$$NPV = \sum_{i=1}^{n} PV_i \qquad \text{(Eq. 8.1)}$$

Such as given by the example,

$NPV = PV_1 + PV_2 + PV_3 + PV_4$

Where,

PV_1 = Initial cost
PV_2 = Annual maintenance
PV_3 = Cost of road expansion (reconstruction)
PV_4 = Annual maintenance from expansion to remaining life cycle

Probabilistic and deterministic models for life cycle analysis can also be utilized in the evaluation. It is, however, fundamental to use a uniform method to evaluate all alternatives to remove any bias between the data of alternatives such that the regret factors can be evaluated also based on the confidence level of the expected net present value costs of the project when entered into the pool of performance indicators.

8.5 Time as a Factor of Decision

The factor of time is also a very important aspect in decision-making. As discussed in Chapter 2, the case study in the City of Plzeň in the Czech Republic is a typical case of how time was ultimately the main factor for the final decision and outcome of the decision process between roads construction alternatives.

As discussed in the previous section, the project duration alone reflects on the net present value of the roads projects under study, since the real cost of the project does not necessarily reflect the nominal value, and therefore the comparison would not be very accurate due to the time.

However, in this section, the factor of time represents more of the urge of completing a project at a specific time to meet certain deadlines, such as traffic calming, reducing congestion which is having adverse effect on the economy, hosting the Olympic Games, or any other reason that may seem critical to the decision-maker.

Time may also affect the payment scheduling and therefore, the required budget, cash flow, and other accounting and financing processes during the construction of the road. Some decisions may be made to certain limitations in these factors as when a project may start and when it should be complete due to financial pressures.

In the classical view, time and quality are very much related with each other. The faster the job is done, the less the quality. However, with modern technology, this is not always true. Modern technology has allowed for faster jobs to be done with even better quality. Nevertheless, in decision-making, it is sometimes important that a task is completed as soon as possible due to certain deadlines to meet with other projects in the area, to solve critical congestion that would have adverse affects economically, or to meet certain political gain by completing a highway project at a certain time.

Bromilow (1974) has established a mathematical model that provides the relationship between completed construction cost and the time taken to complete a construction project. Subsequently the model was updated by Bromilow et al. (1980) as the following:

$$T = K \cdot C^{B} \qquad \text{(Eq. 8.2)}$$

Where,

T = duration of construction period from the date of possession of site to substantial completion in working days.

K = a constant indicating the general level of time performance per millions in currency.

B = a constant describing how the time performance is affected by the size of the construction project measured by its cost.

The model signifies that the duration of a construction project completion time is a function of its cost. This quantifies the effect of cost due to time, whether a road can be completed within a specific time frame or the regret that would be assessed due to exceeding the promised time of completion. This model allows a probable duration of project time on working days, given the estimated cost. Similar research has been done by Ireland (1986) to predict construction time for high-rises, while Kaka and Price (1991) have done the same construction of both buildings and roads. Other research by Kumaraswamy and Chan (1995), Chan (1999), and Choudhury et al. (2002) established similar surveys for the relationship between time and cost in the various construction industries worldwide. However, it is critical to note that the accuracy of the data obtained by any of the models may not be high due to the relationship between attitude of the workers, such as construction union strikes, and management practices applied in the construction field and the time duration of the completion of construction (Ireland 1986, Nkado 1995).

The choice of crew size, equipment, and construction method to complete activities within a specific period of time directly affects the cost of construction. Contractors try fervently to optimize production within the given resources to complete a project within a specific duration.

Another important note to consider is the traffic impact on construction, sometimes referred as construction congestion cost. The reality of this cost is how much a road user is being delayed due to the road construction. This is important to consider in the model as part of the time performance indicator or even an additional performance indicator that specifies the road user cost during construction, which would be in direct relationship with the time period for construction. Though such a criterion can only be included during implementation as it is a factor of the construction method, and not necessarily the road design, it still is crucial to identify whether a specific design has the ability to have an expedited construction to reduce the road user cost. However, not all cases would warrant expediting roadway construction, such as in some rural areas and areas with very low traffic impact during construction.

Based on the notion of the effect of time of completion of a roads construction, a model is established and used that would adequately affect the decision, which would be given a weight when evaluating the performance indicator. Just like any other performance indicator, the model for time is selected by the decision-maker. The decision-maker has a specifically further more freedom in the type of model to be used for the time performance indicator that could be subject to a linear

model, exponential, logarithmic, or any other that may be found to best represent the effect of the time variable in the construction, and then later adding the weight of the time factor in the evaluation of the performance indicator.

When evaluating regret factor for the time of completion, it is important to note the expected time for completion and the risks involved with delays. This can be placed in a probabilistic model in assessing the probability of delay and its duration. Furthermore, the model to be used would therefore, affect the amount of expected error and uncertainties that would involve the project scheduling for each alternative, such as the availability of resources, such as workers and construction materials, as well as other uncertainty factors. The Big Dig project in Boston, for example, has shown that delays in construction duration can be affected due to the uncertainties and risks involved during field work, such as the discovery of sunken ships in land reclamation areas, the release of underground toxins, etc. Therefore, considering the effects of time of completion in some critical projects cannot be overlooked and may have weights that would compete with other factors, such as the effect on planning, economy, and environment, as well as traffic flow and safety.

9. Conclusion

9.1 Evaluation of Road Design and Construction Alternatives

Deciding between different road designs is usually not a simple problem, as it is a complex decision that concerns many different factors, some of which depends on the politics even more than it would depend on the actual technical benefit from such a project. Several performance indicators are used by decision-makers to have a broader understanding of what is the best alternative to choose among many. This study introduces a more systematic approach of evaluating between different alternatives. Although this approach can be expanded for any type of decision-making with various types of performance indicators, the focus in this study is mainly for roads construction alternatives.

Any road project may have a direct influence on the planning of the area, which would also include the environmental aspects, such as the effects on the flora and fauna, as well as air quality issues, which is one of the most important aspects to consider in construction of roads. Different data and models have been introduced in this study and to illustrate the extensive horizon in the complexity of decision-making. This is to demonstrate how values obtained from these performance indicators using whichever model the decision-maker chooses are implemented in the regret model.

The main factors that have been a focus of this study are i) planning, ii) traffic flow, iii) traffic safety, iv) construction economics, and v) time. However, the regret model introduced does not necessarily only envelope those factors, neither does it require all the above factors to exist for a better evaluation. However, the decision-maker has the liberty to choose between the above factors or even add more as it would be deemed necessary. Each performance indicator is given a weight that provides its relative importance with other factors evaluated. It can be imagined that political leaders may add a performance indicator to the above that would include the attitude of the people towards such a project.

9.2 Regretful Decision Making

All decisions made can be regretted, including the decision of not making any. When evaluating alternatives, people regularly look at what would give them the highest gain. Those people are the optimistic and opportunistic type. However, this type does not necessarily be practical, because they would be interested in the highest gain no matter at what cost. A more practical method that investors do is by forming indicators that make them understand the relationship between cost versus benefit. Most investors calculate ratios, such as Return-on-Investment (ROI) index, to understand how much profit is expected from the investment they make. Other individuals seek the least loss. They are known as the pessimistic type, and that as well may not be the best method to evaluate investments on the infrastructure using public funds.

In this study, a regret function has been formed to have a broader understanding of how the regret factor influences decisions in a more practical way for infrastructure investments involving public funds. The main concept behind this is that when dealing with infrastructure investments, flexibility of the design is very important for future expansions, in case they would require a higher capacity in the future. In general, the rule is if a decision need not be regretted, or to reduce the degree of regret, then the best decision would be the decision that can easily be changed. This is very important, since traffic forecasting may not always be accurate. However, this statement is not to be said liberally, because it would still depend on the cost of making a flexible decision compared to the cost of being inflexible. Similarly in the business field, discounted tickets purchased are usually unchangeable.

The mathematical concepts of decision theory have been found to be the best quantitative method to be used in the study and include the regret factor in the decision-making process. A weighted regret matrix has been formulated that provides a systematic ranking system in the evaluation of various road construction designs. The synthesis of probability of potential outcomes into the formulation of the performance indicator provides a powerful tool in the evaluation of the performance indicators.

Due to uncertainties, it is very difficult to reach perfection in any decision. However, evaluating those uncertainties are the basis of formulating a regret matrix that allows decision-makers understand the

complexity of the confidence level given to each performance indicator used in the assessment of alternatives.

9.3 Traffic Safety

When designing new roads, traffic engineers emphasize significantly in traffic flow compared to traffic safety. Hence, there are ample research in computing performance indicators that determine the traffic flow, which include levels of service, delay, number of stops, and others. During the course of this research, it has been found that there is a lacking in a method to evaluate traffic safety.

A method to assess a performance indicator has been established based on specific criteria that directly influence traffic safety, which includes the following factors:

1. The density of traffic conflict points within a section of road.
2. The spacing between one conflict point and another.
3. The speed of both vehicles entering the conflict point.
4. The type of conflict point (i.e. diverging, crossing, or merging).
5. The approach angle of both vehicles with respect to each other.
6. The volume of traffic that share the conflict point.
7. The probability of crash.
8. The Time-to-Collision (TTC).
9. Expected severity of crashes.
    a. Fatalities
    b. Injuries
    c. Property damage
10. Signal phasing

A mesh of the above criteria defined quantitatively provides with a performance indicator for traffic safety that is used to evaluate different alternatives. This allows a simplified method to identify a traffic safety performance indicators based on the above criteria.

9.4 Future Research

The word research is an oxymoron in the etymology of the English language, as it assumes that it re-searches what has already been searched. Nevertheless, research is a systematic investigation to find facts that are usually new. Also, perfection is not a human trait. All research builds on another. In this study, previous studies were investigated thoroughly to build a new method. There is always room to further refine the set of procedures identified in this study.

Since regret is identified due to uncertainties, more research in reducing the amount of uncertainties or even further identifying better quantitative models to assess uncertainties is necessary. Although in this study a procedure to place a regret matrix to evaluate performance indicators in assessing various road design alternatives is constructed, it assumes that there is a level of uncertainty. The objective for perfection is to have no regrets by having perfect models with absolutely no uncertainties. Therefore, any research that helps in the reduction of the amount of expected regret in the evaluation of each alternative is necessary. Though in this study the regret function is focused mainly on road alternatives, it is constructed in a very generic method that would allow it to be applied in various fields and performance indicators. Thence, more

research in the future on how to apply the methodology for diverse methods is important.

Further research in the advancement of fuzzy logic, while utilizing the regret matrix, is necessary. Identifying the relative nearness of results that would comparatively assess alternatives as statistically equivalent is essential in the evaluation of the regret matrix.

The traffic safety quantitative procedure need to be further tested for various road designs. This study has developed a generic process in evaluating a performance indicator for traffic safety. However, different road designs may require the usage of certain constants in the evaluation procedure proposed. Hence, further development in the proposed methodology need to be made, especially to reduce the level of uncertainty which would directly affect the regret model proposed in this study.

Since data output is only as good as data input, then it is important to note that more comprehensive research needs to be extended for each of the models that would be used in obtaining the performance indicator. The higher the accuracy, the lower is the regret. The lower the regret, the better conclusive decisions are organized, benefiting both the decision-makers and the users.

REFERENCES

Adeli, H., and Karim, A. (1997). "Scheduling/cost optimization and neural dynamics model for construction projects." *Journal of Construction Engineering and Management*, 123(4): 450 – 458.

Agumya, A., and Hunter G.J. (2002). "Responding to the consequences of uncertainty in geographical data." *International Journal of Geographic Information Science*, 16(5): 405 – 417.

Ahmad, I. (1992). "Contingency allocation: a computer-aided approach." *Association for the Advancement of Cost Engineering (AACE) Transactions*, F.4: 1 – 7.

Aibinu, A. A., and Jagboro, G. O. (2002). "The effects of construction delays on project delivery in Nigerian construction industry." *International Journal of Project Management*, 20: 593 – 599.

Alkass, S., and Harris, F. (1991). "Development of an Integrated System for Planning Earthwork Operations in Road Construction." *Construction Management and Economics*, E & FN Spon, 9: 263 – 289.

Allen, et. al. (1978). "Analysis of Traffic Conflicts and Collisions." TRR 667, Transportation Research Board (TRB).

Anand, P. (1987). "Are the preference axioms really rational?" *Theory and Decision*, 23: 189 – 214.

Anderson, A., and Russell, J. (2001). "Guidelines for warranty, multiparameter, and best value contracting." *NCHRP Report No. 451*, National Cooperative Highway Research Program, Washington, D.C.

American Association of State Highway and Transportation Officials (AASHTO). (2003). *User Benefit Analysis for Highways*, AASHTO, Washington, D.C, August 2003.

Augusti, G., Ciampoli, M., and Frangopol, D. M. (1998). "Optimal planning of retrofitting interventions on bridges in a highway network." *Engineering Structures*, 20(11): 933 – 939.

Baccarini, D. (2005). "Understanding Project Cost Contingency – A Survey." *Proceedings of International Construction Conference*, Brisbane, Australia.

Bacon, R. R., and Bessant-Jones. (1998). "Estimating construction costs and schedules: experience with power generation projects in developing countries." *Energy Policy*, 26(4): 317 – 333.

Baker. (1972). "An Evaluation of the Traffic Conflicts Technique." TRR 384, Transportation Research Board (TRB).

Banzhaf, H. Spencer, and Jawahar, Puja. (2005). "Public benefits of Endeveloped Lands on Urban Outskirts: Non-Market Valuation Studies and their Role in Land Use Plans." Resources for the Future.

Barberis, N., Huang, M., and Thaler, R. H. (2006). "Individual preferences, monetary gambles, and stock market participation." *American Economic Review*, 96: 1069 – 1090.

Batty, M. and Xie, Y. (1994a). "Modeling Inside GIS: Part 1. Model Structures, Exploratory Spatial Data Analysis and Aggregation." International Journal of Geographic Information Systems, 8(3): 291 – 307.

Batty, M. and Xie, Y. (1994b). "Urban Analysis in a GIS Environment: Population Density Modelin Using ARC/INFO." In S. Fotheringham and P. Rogerson (eds), *GIS and Spatial Analysis*, Taylor and Francis, London, pp. 189 – 219.

Bell, D. E. (1982). "Regret in decision making under uncertainty." *Operations Research*, 30: 961 – 981.

Bell, D. E. (1983). "Risk premiums for decision regret." *Management Science*, 29: 1156 – 1166.

Bell, D. E. (1985). "Disappointment in decision making under uncertainty." *Operations Research*, 33: 1 – 27.

Bellman, R. E., and Zadeh, L. A. (1970). "Decision making in a fuzzy environment." *Management Science*, 17: 141 – 164.

Bhasakar, A., Chung, E., Kuwahara, M., and Oshino, Y. (2004). "Areawide Road Traffic Noise Contour Maps." *Proceedings of 10th World Conference on Transport Research*. Istanbul, Turkey.

Bishr, Yaser. (1998). "Overcoming the semantic and other barriers to GIS interoperability." *Journal of Geographic Information Science*. 12(4): 373 – 402.

Bonham-Carter, G. F. (1994). *Geographic Information Systems for Geoscientists*. Pregamon, Ottawa, p. 398.

Brim, Orville G. (1962). "Personality and Decision Processes," *Studies in the Social Psychology of Thinking*. Stanford.

Bromilow, F. J. (1974). "Measurement and scheduling of construction time and cost performance in building industry" *The Chartered Builder*, pp. 10.

Bromilow, F. J., Hinds, M. F., and Moody, N. F. (1980). "Australian Institute of Quantity Surveyors: survey of building contract time performance." *The Building Economist*, pp. 79 – 82.

Burns, S., Liu, L., and Feng, C. (1996). "The LP/IP hybrid method for construction time-cost trade-off analysis." *Construction Management and Economics*, 14: 265 – 276.

Burrough, P. A. (1986). "Towards a new public management model: beyond managerialism and its critics." *Australian Journal of Public Administration*, 52(2): 135 – 148.

Burroughs, S. E., and Juntima, G. (2004). "Exploring techniques for contingency setting." *Association for the Advancement of Cost Engineering (AACE) Transactions*, EST.03: 1 – 6.

Cai, S. J. (1993). "Grey system theory applied to rock mechanics." *International Journal of Rock Mechanics and Mineral Science and Geomechanics*, 30(4): 473 – 478.

Cervero, Robert., and Hansen, Mark (2000). "Road supply-demand relationships: sorting out casual linkages." *Institute of Transportation Studies Report*, University of California, Berkeley, California, Oct. 2000.

Chakhar, S., Mousseau, V., Pusceddu, C., and Roy, B. (2005). "Decision map for spatial decision making and urban planning." The 9th International Computers in Urban Planning and Urban Management Conference (CUPUM '05), London, UK, July 29 – Aug. 1, 2005.

Chan, A. P. C. (1999). "Time-cost relationship of public sector projects in Malaysia." *International Journal of Project Management*, 19: 223 – 229.

Chan, T. O., and Williamson, I. P. (1995). "Justification of GIS as an infrastructure investment – some observations regarding GIS management in Victoria." In G. J. Hunter (Ed.), Proceedings of the 23rd Annual International Conference and Technical Exhibition of the Australasian Urban and Regional Information Systems Association Incorporated, Melbourne, pp. 492 – 503.

Chan, W., Chua, D., and Kannan, G. (1996). "Construction resource scheduling with genetic algorithms." *Journal of Construction Engineering and Management*, 122(2): 125 – 132.

Chang, I. H. (2000). "Applications of grey theory and multiobjective programming towards airline network design." *European Journal of Operations Research*, 127: 44 – 68.

Chang, N. B., Yeh, S. C., and Wu, G. C. (1999). "Stability analysis of grey compromise programming and its application to watershed landuse planning." *International Journal of Systems Science*, 30(6): 571 – 589.

Chen, D., and Hartman, F. T. (2000). "A neural network approach to risk assessment and contingency allocation." *AACE Transactions*, Risk.01: 01 – 6.

Cheung, K. K. T. (2005). "Development and Testing of a Method for Forecasting Prices of Multi-Storey Buildings during the Early Design Stage: The Storey Enclosure Revisited," PhD thesis, Queensland University of Technology, Australia.

Choudhury, I., Khan, M. M., and Matin, A. (2002). "Relationship between construction time and project cost of health sector construction works in Bangladesh." *Proceedings of the 38th Annual Conference of the Associated Schools of Construction*, Roanoke, Virginia.

Clark, D. E. (2001). "Monte Carlo analysis: ten years of experience." *Cost Engineering*. 43(6): 40 – 45.

Corner, R. J., Hickey, R. J., Cook, S. E. (2002). "Knowledge Based Soil Attribute Mapping in GIS: The Expector Method." *Transactions in GIS*. 6(4): 383 – 402.

Crosetto, M., and Taranola, S. (2001). "Uncertainty and sensitivity analysis: Tools for GIS-based model implementation." *International Journal of Geographical Science*, 15(5): 415 – 437.

Curran, M. W. (1989). "Range Estimating." *Cost Engineering*, 31(3): 18 – 26.

Daganzo, C. F. and Sheffi, Y. (1977). "On Stochastic Models of Traffic Assignment." *Transportation Science*, 11(3): 253 – 274.

Davis, T. J., and Keller, C. P. (1997). "Modelling and visualizing multiple spatial uncertainties." *Computers and Geosciences*, 23(4): 397 – 408.

Deb, K. (2001). *Multiobjective optimization using evolutionary algorithms*, Wiley, New York, NY.

Deb, K., Agrawal, S., Pratap, A., and Meyarivan, T. (2001). "A fast elitist nondominated sorting genetic algorithm for multiobjective optimization." *KANGAL Report No. 200001*, Genetic Algorithm Laboratory, Indian Institute of Technology, Kanpur, India.

Deng, J. (1985). *Grey system fundamental method*, Huazhong Polytechnic University Press, Wuhan, China.

Dey, P., Tabucanon, M. T., and Ogunlana, S. O. (1994). "Planning for project control through risk analysis: a petroleum pipelaying project." *International Journal of Project Management*, 12(1): 23 – 33.

Diekmann, J. E. (1983). "Probabilistic estimating: mathematics and applications." *Journal of Construction Engineering and Management*, 109(3): 297 – 308.

Diekmann, J. E., and Featherman, W. D. (1998). "Assessing cost uncertainty: lessons from environmental restoration projects." *Journal of Construction Engineering and Management*, 124(6): 445 – 451.

Dittmer, S. L., and Jensen, F. V. (1997). "Tools for Explanation in Bayesian Networks with Application to an Agricultural Problem." *Proceedings of the 1st European Conference of Information Technology in Agriculture*. Copenhagen, Denmark, June 15 – 18, 1997.

Drazen, Prelec. (1998). "The probability weighting function." *Econometrica*, 66: 497 – 527.

Dubois, Didier, and Prade, Henri. (1988). "Decision evaluation methods under uncertainty and imprecision." In Kacprzyk, J. and Fedrizzi, M. (eds.) *Combining Fuzzy Impression with Probabilistic Uncertainty in Decision Making*, pp. 48 – 65.

Easa, S. M. (1989a). "Resource leveling in construction by optimization." *Journal of Construction Engineering and Management*, 115(2), 302 – 316.

Easa, S. M. (1989b). "Simplifying Roadway Cross Sections Without Reducing Volume Accuracy." *Canadian Journal of Civil Engineering*, CSCE, 16: 483 – 488.

Easa, S. M. (1992). "Estimating Earthwork Volumes of Curved Roadways: Mathematical Model." *Journal of Transportation Engineering*, ASCE, 118(6): 834 – 849.

Edwards, W. and Fasolo, B. (2001). "Decision Technology." *Annual Review of Psychology*, 52: 581 – 606.

Elhag, T. M. S., and Boussebaine, A. H. (1998). "Factors affecting cost and duration of construction projects." EPSRC Research Rep. Phase (1), School of Architecture and building Engineering, University of Liverpool, Liverpool, UK.

El-Rayes, K. (2001). "Optimum planning of highway construction under the A+B bidding method." *Journal of Construction Engineering and Management*, American Society of Civil Engineers (ASCE), 127(1): 18 – 27.

El-Rayes, K., and Hyari, K. (2002). "Automated DSS for lighting design of nighttime operations in highway construction projects." *Proceedings, 19th International Symposium on Automation and Robotics in Construction.*

El-Rayes, K., and Hyari, K. (2004). "CONLIGHT: Lighting design model for nighttime highway construction." *Journal of Construction Engineering and Management*, American Society of Civil Engineers (ASCE), 131(4): 467.

El-Rayes, K., and Moselhi, O. (2001). "Optimizing Resource Utilization for Repetitive Construction Projects." *Journal of Construction Engineering and Management*, American Society of Civil Engineers (ASCE), 16(4): 433 – 446.

Ellis, R., and Amos, S. (1996). "Development of work zone lighting standards for nighttime highway work." *Transportation Research Record 1529*, Transportation Research Board, Washington, D.C.

Engineering News Record (ENR). (2002). "Springfield mixing bowl tosses up a medley of challenges: Virginia DOT and contractors strive to untangle I-15 web."

Epps, J. and Corey, M. (1990). "Cut and Fill Calculations by Modified Average-End-Area Method." *Journal of Transportation Engineering*, ASCE, 116(5): 683 – 689.

Fan, L., Ho, C., and NG, V. (2001). "A Study of Quantity Surveyors' Ethical Behaviour." *Construction Management and Economics*, E and FN Spon, Vol. 19, pp. 19 – 36.

Fancher, P., Bogard, S., Bareket, Z., Hagan, M., and Ervin, R. (1997). "Data processing procedures for identifying driver / vehicle properties associated with the control of headway." IEEE Conference on Intelligent Transportation Systems, Boston, MA, Nov. 1997.

Fausold, Charles, and Lileiholm, Robert. (1996). "The Economic Value of Open Space: A Review and Synthesis." Lincoln Institute.

Fayek, A. (1998). "Competitive bidding strategy model and software system for bid preparation." *Journal of Construction Engineering and Management*, 124(1): 1 – 10.

Fechner. (1860/1966). *Elements of Psychophysics*, Holt, Rinehart, and Winston, New York.

Feng, C., Liu, L., and Burns, S. A. (1997). "Using genetic algorithms to solve construction time-cost trade-off problems." *Journal of Computational Civil Engineering*, 11(3): 184 – 189.

Feng, C., Liu, L., and Burns, S. (2000). "Stochastic construction time-cost trade-off analysis." *Journal of Computational Civil Engineering*, 14(2): 117 – 126.

Ferson, S., and Ginzburg, L.R. (1996). "Different methods are needed to propagate ignorance and variability." *Reliability Engineering and System Safety*, 54: 133 – 144.

Federal Highway Agency (FHWA) (1995). *Manual of Uniform Traffic Control Devices*, FHWA, U.S. Department of Transportation, Washington D.C.

Fishburn, P. C. (1991). "Nontransitive preferences in decision theory." *Journal of Risk and Uncertainty*, 4: 113 – 134.

Galadari, A. (2003). "Integration of 4D CAD into Geographic Information Systems (GIS) for Construction Planning and Management." Master Report: University of Colorado.

Galadari, A. (2004). "Construction Management in GIS Using 2D Simulation and 4D CAD GIS." Proceedings of the 2004 ESRI Middle East and Africa User Conference, 7 – 9 Dec. 2004.

Glauz, W., and Migletz, D. (1980). "Application of Traffic Conflicts at Intersections." National Cooperative Highway Research program (NCHRP) 219.

Golabi, K., Thompson, P., and William, H.A. (1993). "Pontis Version 2.0 Technical Manual, A Network Optimization System for Bridge Improvements and Maintenance, Report No. FHWA-SA-94-031, to the Federal Highway Administration (FHWA), by Optima, Inc., San Francisco, CA, and Cambridge Systematics, Inc., Cambridge, MA, December 1993.

Goeree, J., Holt, C. A., and Palfrey, T. (2003). "Risk averse behavior in generalized matching pennies games." *Games and Economic Behavior*, 45: 97 – 113.

Goldberg, D. E. (1989). *Genetic algorithms in search, optimization, and machine learning*, Addison-Wesley, New York, NY.

Gollier, J., and Salanié, B. (2006). "Individual decisions under risk, risk sharing and asset prices with regret." *Working Paper*, University of Toulouse and INSEE.

Gomar, J., Haas, C., and Morton, D. (2002). "Assignment and allocation optimization of partiallymultiskilled workforce." *Journal of Construction Engineering and Management*, 128(2): 103 – 109.

Goodchild, Michael F., Egenhofer, Max J., and Fegeas, Robin. (1997). "Interoperating GISs." Report of a Specialist Meeting Held under the Auspices of the Varenius Project Panel on Computational Implementations of Geographic Concepts. December 5 – 6, 1997, Santa Barbara, CA.

Gurnani, Ashwin P., and Lewis, Kemper. (2005). "Robust multiattribute decision making under risk and uncertainty in engineering design." *Engineering Optimization*, 37(8): 813 – 830.

Gurnani, A., See, T-K, and Lewis, K. (2003). "An approach to robust multiattribute concept selectioin." In *ASME Design Automation Conference*, Paper no. DETC/DAC-48707.

Hackney, J. W. (1985). "Applied contingency analysis." *AACE Transactions*. B: 1 – 4.

Hardaker, J. B., Huirne, R. B. M., and Anderson, J. R. (1997). *Coping with Risk in Agriculture*, CAB International, Wallingford, UK: 274.

Hartman, F. T. (2000). *Don't Park Your Brain Outside*, Project Management Institute, Upper Darby, PA.

Hartigan, J. A. (1983). *Bayes Theory*, Springer-Verlag, New York.

Hartgen, D. T., and Talvitie, A. P. (1995). "Comparative performance of transportation systems: Pitfalls and prospects." Proceedings, World Conference on Transit Research, Sydney, Australia.

Hartgen, D. T., Bowman, V. B., and Horner, M. W. (1997). "Baseline market forecasts for state highway construction engineering, maintenance, and administration programs 1997 – 2001." Transportation Publication Number 151, Center for Interdisciplinary Transportation Studies, University of North Carolina, Charlotte, N.C.

Hauer, E. (1992). "Empirical Bayes Approach to the Estimation of 'Unsafety': The Multivariate Regression Method." *Accident Analysis and Prevention*, 24(5): 457 – 477.

Hayward, J. C. (1972). "Near-miss Determination through Use of a Scale of Danger." Highway Research Record (HRR), Transportation Research Board (TRB), 384, pp. 24 – 34.

Healey, P. (1997). *Collaborative Planning*. Macmillan, London, UK.

Hegazy, T. (1999). "Optimization of resource allocation and leveling using genetic algorithms." *Journal of Construction Engineering and Management*, 125(3): 167 – 175.

Hegazy, T., and Ayed, A. (1998). "Neural network model for parametric cost estimation of highway projects." *Journal of Construction Engineering and Management*, 124(3): 210 – 218.

Hegazy, T., and Ersahin, T. (2001). "Simplified spreadsheet solutions. II: Overall schedule optimization." *Journal of Construction Engineering and Management*, 127(6): 469 – 475.

Hegazy, T., and Wassef, N. (2001). "Cost optimization in projects with repetitive nonserial activities." *Journal of Construction Engineering and Management*, 127(3): 183 – 191.

Herbsman, Z. (1986). "Model for forecasting highway construction cost." *Transportation Research Record 1056*, Transportation Research Board (TRB), Washington, D.C., 47 – 54.

Herbsman, Z. (1995). "A+B bidding method – Hidden success story for highway construction." *Journal of Construction Engineering and Management*, 121(4): 430 – 437.

Heuvlink, G. (1998). *Error Propagation in Environmental Modelling with GIS*, Taylor and Francis, London, UK, pp. 144.

Hey, J. D., and Orme, C. (1994). "Investigating generalizations of expected utility theory using experimental data." *Econometrica*, 62: 1291 – 1326.

Horst, A. R. (1990). "A Time-based Analysis of Road User Behavior at Intersections." *Proceedings of the 3rd Workshop of International Cooperation on Theories and Concepts in Traffic Safety*, Cracow.

Huang, G. H. (1996). "A grey hop, skip and jump approach: generating alternatives for expansion planning of waste management facilities." Canadian Journal of Civil Engineering, 23: 1207 – 1219.

Hurwicz, L. (1951). "Optimality criteria for decision making under ignorance." *Cowles Commission Discussion Paper 370*, Chicago.

Hyden, C. (1996). "Traffic conflicts techniques: State-of-the-art." In: Topp H.H. (Ed.), (1998). Traffic Safety Work with video-processing. University Kaiserslautem. Transportation Dept., 1998, Green Series No. 43.

Innes, J. (1995). "Planning theory's emerging paradigm: Communicative action and interactive practice." *Journal of Planning Education and Research*. 14(3): 183 – 190.

Ireland, V. (1986). "A comparison of Australia and US building performance for high-rise buildings." University of technology, Sydney, Australia: School of Building Studies.

Israelsen, T., and Fredriksen, R. (2005). "The Use of GIS in Transport Modeling." In *GIS, Spatial Analysis, and Modeling, ed.* D. J. Maguire, M. Batty, and M. F. Goodchild, pp 265 – 287. ESRI Inc., Redlands, CA.

Jareidi, M., Plummer, R., and Aber, M. (1995). "Incentive/disincentive guidelines for highway construction contracts." *Journal of Construction Engineering and Management*, 121(1): 112 – 120.

Jha, M.K. (2000). *A Geographic Information Systems-Based Model for Highway Design Optimization*, Ph.D. Dissertation, University of Maryland, College Park, MD.

Jha, M.K., McCall, C., and Schonfeld, P. (2001). "Using GIS, genetic algorithms, and visualization in highway development." *Computer-Aided Civil and Infrastructure Engineering*, 16(6): 399 – 414.

Jong, J.C. (1998). *Optimizing Highway Alignments with Genetic Algorithms*, Ph.D. Dissertation, University of Maryland, College Park, MD.

Jong, J.C., Jha, M.K., and Schonfeld, P. (2000). "Preliminary highway design with genetic algorithms and geographic information systems." *Computer-Aided Civil and Infrastructure Engineering*, 15(4): 261 – 271.

Jongeneel, C.J.B. and Koppelaar, H. (1999). "Gödel Pro and Contra AI: Dismissal of the case." *Engineering Applications of Artificial Intelligence*, 12: 655 – 659.

Jungermann, H. (1983). "The two camps on rationality." In *Decision Making Under Uncertainty*, Scholz, R.W. (ed.) Elsevier, Amsterdam, Netherlands: 450 – 458.

Kahneman, D. A. and Tversky, A. (1979). "Prospect theory: An analysis of decision under risk." Econometrica, 47: 263 – 291

Kaka, A., and Price, A. D. F. (1991). "Relationship between value and duration of construction projects." *Construction Management and Economics*, 9: 383 – 400.

Kaub, A. R. (1987). "A Design Warrant for Auxiliary Passing Lanes on Rural Two-lane Highways." University of Wisconsin – Madison and UMI Dissertation Service # 8720466.

Kaub, A. R. (1996). "A probable conflict opportunity model to estimate annual intersection and access accidents for any volume, geometry, speed and traffic control." *2nd National Access Management Conference Compendium of Papers*, Vail, Colorado.

Keeney, R., and Raiffa, H. (1993). In *Decisions with Multiple Objectives: Preferences and Value Tradeoffs*, Cambridge University Press: Cambridge, UK.

Kim, G. H., An, S. H., and Kang, K. I. (2004). "Comparison of construction cost estimating models based on regression analysis, neural networks, and case-based reasoning." *Building and Environment*, 39: 1235 – 1242.

Kirk, Stephen J., and Dell'Isola, Alphonse J. (1995). *Life Cycle Costing for Design Professionals*. 2nd Ed. McGraw-Hill Inc., New York.

Klosterman, R. (1998). "Computer Applications in Planning." *Environment and Planning B*, Anniversary Issue: 32 – 36.

Koehn, E., Fallon, B., Seling, F., and Young, R. (1978). "Cost of delays in construction." *Journal of Construction Division*, American Society of Civil Engineering (ASCE), 104(3): 323 – 331.

Koppula, S. D. (1981). "Forecasting engineering costs: two case studies." *Journal of Construction Division*, American Society of Civil Engineering (ASCE), 107(4): 733 – 743.

Kumaraswamy, M. M., and Chan, D. W. M. (1995). "Determinants of construction duration." *Construction Management and Economics*, 13: 209 – 217.

Laplace, P. S. (1825). *Essai Philosophique sur les probabilités*. Bachelier, Paris, 5th edition. English translation with notes by A. I. Dale: Laplace, P. S. (1825). *Philosophical Essay on Probabilities*. Springer-Verlag.

Larrick, R. P. (1993). "Motivational factors in decision theories: The role of self-protection." *Psychological Bulletin*, 113: 440 – 450.

Leach, L. P. (2003). "Schedule and cost buffer sizing: how to account for the bias between project performance and your model." *Project Management Journal*, 34(2): 34 – 47.

Lee, D. B. (1973). "Requiem for large-scale models." *Journal of American Institute of Planners*, 39: 163 – 178.

Leu, S., and Hwang, S. (2001). "Optimal repetitive scheduling model with shareable resource constraint." *Journal of Construction Engineering and Management*, 127(4): 270 – 280.

Li, H., and Azarm, S. (2000). "Product design selection under uncertainty and with competitive advantage." *Journal of Mechanical Design*, 122(4): 411 – 418.

Li, H, and Love, P. (1997). "Using improved genetic algorithms to facilitate time-cost optimization." *Journal of Construction Engineering and Management*, 123(3): 233 – 237.

Li, H, Cao, J., and Love, P. (1999). "Using machine learning and genetic algorithm to solve time-cost trade-off problems." *Journal of Construction Engineering and Management*, 125(5): 347 – 353.

Loomes, G., Starmer, C., and Sugden, R. (1991). "Observing violations of transitivity by experimental methods." *Econometrica*, 59: 425 – 439

Loomes, G. and Sugden, R. (1982). "Regret theory: An alternative theory of rational choice." *Economic Journal*, 92: 805 – 824.

Lorance, R. B., and Wendling, R. V. (1999). "Basic techniques for analysing and presenting cost risk analysis." *AACE Transactions*, Risk.01: 1 – 7.

Mackie, P., and Nellthorp, J. (2001). "Chapter 10: Cost-benefit analysis in transport." *Handbook of Transport Systems and Traffic Control*, K. J. Button and D. A. Hensher, eds., Pergamon, Amsterdam, 143 – 174.

Mak, S., Wong, J., and Picken, D. (1998). "The effect on contingency allowances of using risk analysis in capital cost estimating: a Hong Kong case study." *Construction Management and Economics*, 16: 615 – 619.

Mak, S., and Picken, D. (2000). "Using risk analysis to determine construction project contingencies." *Journal of Construction Engineering and Management*, 126(2): 130 – 136.

Martin, W. A., and McGuskin, N. A. (1998). "Travel estimation techniques for urban planning." *National Cooperative Research Program Report 365*, Transport Research Board (TRB), National Research Council, Washington, D.C.

Maxwell, D., Back, E., and Toon, J. (1998). "Optimization of crew configurations using activity-based costing." *Journal of Construction Engineering and Management*, 124(2): 162 – 168.

McCall, C. (1999). *Cost Effective Computer Visualization for Highway Development*, Master's Thesis, Department of Civil and Environmental Engineering, University of Maryland, College Park, MD.

McDonnel, R., Chung, E. (2001). "Modelling External Factors in Transport." *Proceedings of Conference of Australian Institute of Transport Research*, Monash University, Victoria, Australia.

McGhee, C. C., and Arnold, E. D. (1997). "Review and Evaluation of Methods for Analyzing Capacity at Signalized Intersection." In *Transportation Research Record 1572*, TRB National Research Council, Washington D.C. pp. 160 – 166.

McKelvey, R., and Palfrey, T. (1995). "Quantal response equilibria for normal form games." *Games and Economic Behavior*, 10: 6 – 38.

McKinney, K., and Fisher, M. (1998). "Generating, evaluating, and visualizing construction schedules with 4D-CAD tools." A*utomation in Construction*, 7(6): 433 – 447.

Merrow, E. W., Phillips, K. E., and Myers, C. (1981). *Understanding Cost Growth and Performance Shortfalls in Pioneer Process Plants.* Rand Corp.

Merrow, E. W., and Schroeder. (1991). "Understanding the cost and schedule of hydroelectric projects." A*ssociation for the Advancement of Cost Engineering (AACE) Transactions*, I.3: 1 – 7.

Merrow, E. W., and Yarossi, M. E. (1990). "Assessing project cost and schedule risk." *AACE Transactions*, H.6: 2 – 7.

Michenaud, S., and Solnik, B. (2006). "Applying regret theory to investment choices: Currency hedging decisions." *Working Paper*, HEC-School of Management.

Minchin, R. E., and Smith, G. R. (2001). "Quality-based performance rating of contractors for prequalification and bidding purposes." *PTI 2001-25*, Pennsylvania Transportation Institute, Pennsylvania State University, University Park, PA.

Minderhood, M. M., and Bovy, P. H. L. (2001). "Extended Time-To-Collision Measures for Road Traffic Safety Assessment." Accident Analysis and Prevention, 33: 89 – 97.

Minieka, E. (1978). "Optimization Algorithms for Networks and Graphs." Marcel Dekker, Inc.

Miotto, A. (2000). "A better image." *Civil Engineering*, 70(1): 42 – 45.

Moore, Terry, and Throsnes, Paul. (1994). "The Transportation / Land Use Connection." American Planning Association, Planning Advisory Service, Report 448/449.

Moselhi, O. (1997). "Risk assessment and contingency estimating." *Association for the Advancement of Cost Engineering (AACE) Transactions*, D&RM/A.06: 1 – 7.

Moselhi, O., and El-Rayes, K. (1993). "Scheduling of repetitive projects with cost optimization." *Journal of Construction Engineering and Management*, 119(4): 681 – 697.

Moudon, Anne Vernez, and Hubner, Michael. (2000). *Monitoring land supply with geographic information systems: Theory, practice, and parcel-based approaches*. Cambridge: Cambridge University Press.

Muearmann, A., Mitchell, O. S., and Volkman, J. M. (2006). "Regret, portfolio choice, and guarantees in defined contribution schemes." *Insurance: Mathematics and Economics*, 39:219 – 229.

Muearmann, A., and Volkman, J. M. (2007). "Regret, pride, and the disposition effect." *Working Paper*, University of Pennsylvania.

Nedovic-Budic, Z. (1998). "The Impact of GIS Technology." *Environment and Planning B*, 25(5): 681 – 692.

Nielsen, Otto Anker. (1995). "Using GIS in Denmark for Traffic Planning and Decision Support." Journal of Advanced Transportation, Special issue on GIS Applications in Transportation Engineering and Planning. 29(3): 335 – 354.

Nielsen, Otto Anker. (1996). "Do Stochastic Traffic Assignment Moels Consider Differences in Road Users Utility Functions?" 24th European Transport Forum (PRTC annual meeting), London, UK. Seminar M.

Nielsen, Otto Anker. (1997a). "Multi-Path OD-Matrix Estimation (MPME) based on Stochastic User Equilibrium Traffic Assignment." TRB-annual meeting, Washington D.C. Pre-prints, Vol. III, No. 0234, January.

Nielsen, Otto Anker. (1997b). "On the distribution of the stochastic componens in SUE traffic assignment models." 25th European Transport Forum (PRTC annual meeting), London, UK. September.

Nielsen, Otto Anker and Frederiksen, Rasmus Dyhr (TetraPlan Lts.). (1997a). "Stochastic User Equilibrium Traffic Assignment with turn-delays in intersections." 7th International Conference on Information Systems in Logistics and Transport, Traffic Assignment Session, Göteborg, June.

Nielsen, Otto Anker, Frederiksen, Rasmus Dyhr (TetraPlan Ltd.), and Simonsen, Nikolaj (Anders Nyvig Ltd.). (1997b). "Using expert system rules to establish data on intersections and turns in road networks." 7th International Conference on Information

Systems in Logistics and Transport, Traffic Assignment Session, Göteborg, June.

Nkado, R. N. (1995). "Construction time-influencing factors: The contractos perspective." *Construction Management and Economics*, 13: 81 – 89.

Norman, A. L. and Shimer, D. W. (1994). "Risk, uncertainty, and complexity." *Journal of Economic Dynamics and Control*, 18(1): 231 – 249.

Oberlander, G. D. and Trost, S. M. (2001). "Predicting accuracy of early cost estimates based on estimate quality." *Journal of Construction Engineering and Management*, 127(3): 173 – 182.

Odeck, J. (2004). "Cost overruns in road construction – what are the sizes and determinants?" *Transport Policy*, 11: 43 – 53.

O'Looney, John. (2000). *Beyond maps: GIS and decision making in local government*. Redlands, CA. ESRI Press.

Oloufa, A. A. (1991). "Triangulation Applications in Volume Calculation." *Journal of Computing in Civil Engineering*, ASCE, 5(1): 103 – 121.

Olson, R. M. and Epps, J. A. (1981). "Construction cost trend." Research Report 214 – 29, Texas A&M University, College Station, TX.

Oort, C. J. (1969). "Evaluation of travel time." *Journal of Transportation Economic Policy*, 3(3): 279 – 287.

Oshino, Y., Kono, S., Ohnishi, H., Sone, T., Tachibana, H. (2000). "Road Traffic Noise Prediction Model (ASJ Model-1998) proposed by the Acoustical Society of Japan – Part 2: Calculation model of sound power levels of road vehicle" *Proceedings of 29th International Congress and Exhibition on Noise Control Engineering*, InterNoise 2000, Nice, France.

Paddock. (1974). "The Traffic Conflicts Technique: An Accident Prevention Method." Bureau of Traffic Control, Ohio Department of Transportation.

Pannel, D.J., Malcolm, B., and Kingwell, R.S. (2000). "Are we risking too much? Perspectives on risk in farm modelling." *Agricultural Economics*, 23(1): 69 – 78.

Papacostas, C. S., and Prevedouros, P. D. (2001). *Transportation engineering and planning.* Prentice-Hall, Upper Saddle River, N.J.

Patrascu, A. (1988). *Construction Cost Engineering Handbook.* M. Dekker, New York, NY.

Pearl, J. (1988). *Probabilistic Reasoning in Intelligent Systems: Networks of Plausible Inference*, Morgan Kaufmann, San Mateo, CA pp. 552

Perkins, S. R., and Harris, J. I. (1968). "Traffic conflict characteristics: Accident potential at intersections." *Highway Research Record 225*, Transportation Research Board (TRB), pp. 45 – 143.

Project Management Institute (PMI). (2004). *A Guide to the Project Management Body of Knowledge.* 3rd Edition. PMI, Newtown Square, PA.

Pugh, D. E., and Halpin, T. J. (1970). "Traffic Conflicts in Washington State." *Unpublished Report*, Washington State Department of Transportation.

Rowe, W.D. (1994). "Understanding uncertainty." *Risk Analysis*, 14(5): 743 – 750.

Savage, L. J. (1951). "The Theory of Statistical Decision." *Journal of the American Statistical Association*, 46: 55 – 67.

Senouci, A., and Eldin, N. (1996). "Dynamic programming approach to scheduling of nonserial linear project." *Journal of Computational Civil Engineering*, 10(2): 106– 114.

Shafer, Glenn. and Pearl, Judea. (eds). (1990). *Readings in Uncertain Reasoning*, Morgan Kaufmann, San Mateo, CA, pp. 768.

Sheffi, Yosef. (1985). *Urban Transportation Networks: Equilibrium Analysis with Mathematical Programming Methods*. Prentice Hall, Inc., Englewood Cliffs, NJ.

Sheffi, Yosef, and Powell, W. B. (1982). "An Algorithm for the Equilibrium Assignment Problem with Random Link Times." Networks, 12(2): 191 – 207.

Simon, Herbert. (1957). *Models of Man.* John Wiley & Sons., Englewood Cliffs, NJ.

Siyam, Y. M. (1987). "Precision in Cross-Sectional Area Calculations on Earthwork Determination." *Journal of Surveying Engineering*, ASCE, 113(3): 139 – 151.

Skitmore, R. M., and Patchell, B. R. (1990). "Developments in contract price forecasting and bidding techniques." In *Quantity Surveying Techniques: New Directions*, Brandon, P. S. (ed.). Blackwell Scientific, London, UK, 75 – 120.

Smith, R. D. (1996). "Is regret theory an alternative basis for estimating the value of health care interventions?" *Health Policy*, 37: 105 – 115.

Sobanjo, J.O. (1991). "A Decision Support Methodology for the Rehabilitation and Replacement of Highway Bridges," Unpublished PhD dissertation presented to the Texas A&M University, College Station, Texas.

Sobanjo, J.O. (1999). "Facility Life-cycle Cost Analysis Based on Fuzzy Sets Theory," Proceedings of the 8th International Conference on Durability of Building Materials and Components, Service Life, and Asset Management: Towards Integration and Application of Service Life Prediction Methods, Vancouver, Canada.

Sonmez, R. (2004). "Conceptual cost estimation of building projects with regression analysis and neural networks." *Canadian Journal of Civil Engineering*, 31(4): 677 – 683.

Stark, R. M., and Mayer, R. H. (1983). *Quantitative Construction Management: Uses of Linear Optimization*. John Wiley & Sons Inc., New York, USA.

Starmer, Chris. (2000). "Developments in non-expected utility theory: the hunt for a descriptive theory of choice under risk." *Journal of Economic Literature*, 38: 332 – 382.

Steenbrink, P. A. (1974). *Optimization of transport networks*. Wiley, New York.

Stevens, J. D. (1995). "Cost estimating and forecasting for highway work in Kentucky." Research Report KTC 95 – 12, Kentucky Transportation Center, University of Kentucky, Lexington, KY.

Sui, D. Z. (1998). "GIS-Based Urban Modeling: Practices, Problems, and Prospects." *International Journal of Geographical Information Science*, 12(7): 651 – 671.

Sullivan, Gregory W. (2005). "A Review of Big Dig Professional Liability Insurance Coverage," Office of the Inspector General, Commonwealth of Massachusetts, June 2005.

Tachibana, H. (2000). "Road Traffic Noise Prediction Model (ASJ Model-1998) proposed by the Acoustical Society of Japan – Part 1: Its structure and the flow of calculation." *Proceedings of 29th International Congress and Exhibition on Noise Control Engineering*, InterNoise 2000, Nice, France.

Thompson, P. A., and Perry, J. G. (1992). *Engineering Construction Risks*. Thomas Telford, London, UK.

Thurston, D.L. (1991). "A formal method for subjective design evaluation with multiple attributes." *Res. Engineering Design*, 3: 105 – 122.

Tomlinson, R. (2003). *Thinking About GIS – Geographic Information Systems Planning for Managers.* ESRI Inc., Redlands, CA.

Topp, H. H. (1998). *Traffic Safety Work with video-processing.* University Kaiserslautem. Transportation Dept., 1998, Green Series No. 43.

Transportation Research Board. (TRB). (2000). Highway capacity manual. *Special Report 209.* TRB., National Research Council, Washington, D.C.

Tversky, A. and Kahnemann, D. (1974). "Judgment under uncertainty: Heuristics and Biases." *Science*, Vol. September.

Tversky, A. and Kahnemann, D. (1992). "Advances in prospect theory: Cumulative representation of uncertainty." Journal of Risk and Uncertainty, 5: 297 – 323.

Tversky, Amos, and Wakker, Peter P. (1995). "Risk Attitudes and Decision Weights." *Econometrica*, 63: 1255 – 1280.

Uesaka, K., Ohnishi, H., Chiba, T., and Takagi, K. (2000). "Prediction and evaluation methods for road traffic noise in built-up areas, inter-noise." *Proceedings of 29th International Congress and Exhibition on Noise Control Engineering*, InterNoise 2000, Nice, France.

United States Department of Transportation (USDOT). (2002). *Life-Cycle Cost Analysis Primer*, USDOT office of Asset Management, August 2002.

Unwin, Stephen D. (1986). "Do your standards make any difference? Asymmetry in preference judgments," *Perceptual and Motor Skills*, 63: 1059 – 1066.

van Arem, B., and De Vos A.P. (1997). "The Effect of a Special Lane for Intelligent Vehicles on Traffic Flows". TNO-INRO Report 1997-02a, Delft, Netherlands.

van Asselt, M.B.A. (2000). *Perspectives on Uncertainty and Risk – The PRIMA Approach to Decision Support*, Kluwer Academic Publishers, Dordecht, pp. 434.

Wakker, P. P., and Deneffe, D. (1996). "Eliciting von Neumann-Morgenstern utilities when probabilities are distorted or unknown." *Management Science*, 42: 1131 – 1150.

Wegener, M. (1998). "Applie models of urban land use, transport and environment: state-of-the-art and future developments." In Lundqvist, L., Mattson, L. –G., and Kim, T. J. (eds.) *Network Infrastructure and the Urban Environment: Recent Advances in Land use / Transportation modelling*, Berlin, Heidelberg, New York: Springer, pp. 245 – 267.

Williams, T. P. (2002). "Predicting completed prost costs using bidding data." *Construction Management and Economics*, 20: 225 – 235.

Williams, T. P. (2003). "Predicting final cost for competitively bid construction projects using regression models." *International Journal of Project Management*, 21: 593 – 599.

Wong, W. (1999). "Gray evaluation method of concrete pavement comprehensive condition." *Journal of Transportation Engineering*, 125(6): 547 – 551.

Yaniv, G. (2000). "Withholding information from cancer patients as a physician's decision under risk." *Medical Decision Making*, 20: 216 – 227.

Yeh, A. (1999). "Urban planning and GIS." In Longley, P., Goodchild, M., Maguire, D., and Rhind, D. (eds.) (1999), *Geographical Information Systems*, Vol. 2, John Wiley & Sons, Inc., New York, pp. 877 – 888.

Yeo, K. T. (2003). "Risks, classification of estimates, and contingency management." *Journal of Management in Engineering*, 6(4): 458 – 470.

Zadeh, L. A. (1965). "Fuzzy Sets." *Information and Control*, 8: 338 – 353.

Zeelenberg, M. (1999). "Anticipated regret, expected feedback and behavioral decision making." *Journal of Behavioral Decision Making*, 12: 93 – 106.

Zeelenberg, M., Beattie, J., van der Pligt, J., and de Vries, N. K. (1996). "Consequences of regret aversion: Effects of expected feedback on risky decision-making." *Organizational Behavior and Human Decision Processes*, 65: 148 – 158.

Zegeer, C., and Dean, R. (1978). "Traffic Conflicts as a Diagnostic Tool in Highway Safety." TRR 667, Transportation Research Board (TRB).

Zeiler, M. (1999). *Modeling Our World: The ESRI Guide to Geodatabase Design*. Redlands, California: ESRI Press.

Zhang, J. X., and Goodchild, M. F. (2002). *Uncertainty in Gepgraphical Information*. New York: Taylor and Francis.

Zitzler, E., Laumanns, M., and Thiele, L. (2001). "SPEA2: Improving the strength Pareto evolutionary algorithm." *TIK-Report No. 103*, Swiss Federal Institute of Technology, (ETH), Zurich, Switzerland.